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AICE* SURVEY OF USSR AIR POLLUTION LITERATURE

Volume V

EFFECTS OF METEOROLOGICAL CONDITIONS AND RELIEF ON AIR POLLUTION; AIR CONTAMINANTS – THEIR CONCENTRATION, TRANSPORT, AND DISPERSAL

Edited By

M. Y. Nuttonson

The material presented here is part of a survey of
USSR literature on air pollution
conducted by the Air Pollution Section
AMERICAN INSTITUTE OF CROP ECOLOGY

This survey is being conducted under GRANT 1 RO1 AP00786 – APC
THE NATIONAL AIR POLLUTION CONTROL ADMINISTRATION

*AMERICAN INSTITUTE OF CROP ECOLOGY
809 DALE DRIVE
SILVER SPRING, MARYLAND 20910

1970

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PREFACE

Much of the background material presented in the prefaces to the preceding volumes of this series is repeated here in view of its relevance to the present volume.

Contamination of the natural environment constitutes a major problem in all industrial regions of the Union of Soviet Socialist Republics (USSR). The country's industry and transport are continually bringing about massive qualitative changes in the habitat of man and vegetation through an ever increasing pollution of air, soil, and streams. In recent years there has been a greater awareness of the immense problems of air and water pollution on the part of the urban and rural administrative agencies as well as on the part of various research institutes of the USSR. There is a mounting demand there to maintain a high quality physical environment. Protective measures against the pollution threat are gradually taking shape. Much relevant air pollution research data are being developed and are apparently put to good use in some parts of this vast and diverse country.

The behavior of atmospheric contaminants, notably gases and fine particles discharged into the air, is similar to that of the air masses near the surface of the earth -- the distribution of the contaminants being influenced by atmospheric stability, wind, precipitation, and topographic features of a given area or region. The most outstanding and dominant characteristic of the atmosphere is its unceasing change, a change resulting from variations of temperature, wind, and precipitation. These meteorological conditions vary widely as a function of latitude, season, and topography. Seasonal as well as diurnal temperature gradients, horizontal and vertical, affect the speed of the wind flow. Generally, the greater the wind velocity the more rapid is the dispersion of pollutants in the atmosphere. In continental areas the temperature gradients and the consequent wind flow increase during the winter season and during the daytime periods, the latter being usually subject to more turbulent winds of higher velocity than those that prevail during night hours that are typically characterized by low-level stability with a minimum dispersal and dilution of the pollutants.

Studies of atmospheric diffusion and air pollution constitute a rapidly developing area of meteorological sciences in the USSR. Determination and analysis of the complex set of meteorological factors causing the processes of atmospheric diffusion are being extensively developed there in conjunction with theoretical and experimental studies of the pattern of propagation of contaminants in the atmosphere.

Most of the reports of investigations brought together in this volume deal with meteorological conditions and relief as factors in propagation and dispersal of air pollutants in a number of areas in the Soviet Union.

A considerable number of these investigations have been conducted in various industrial regions of the USSR, regions that are geographically far apart from each other and subject to distinctly different natural and man-made environmental conditions.

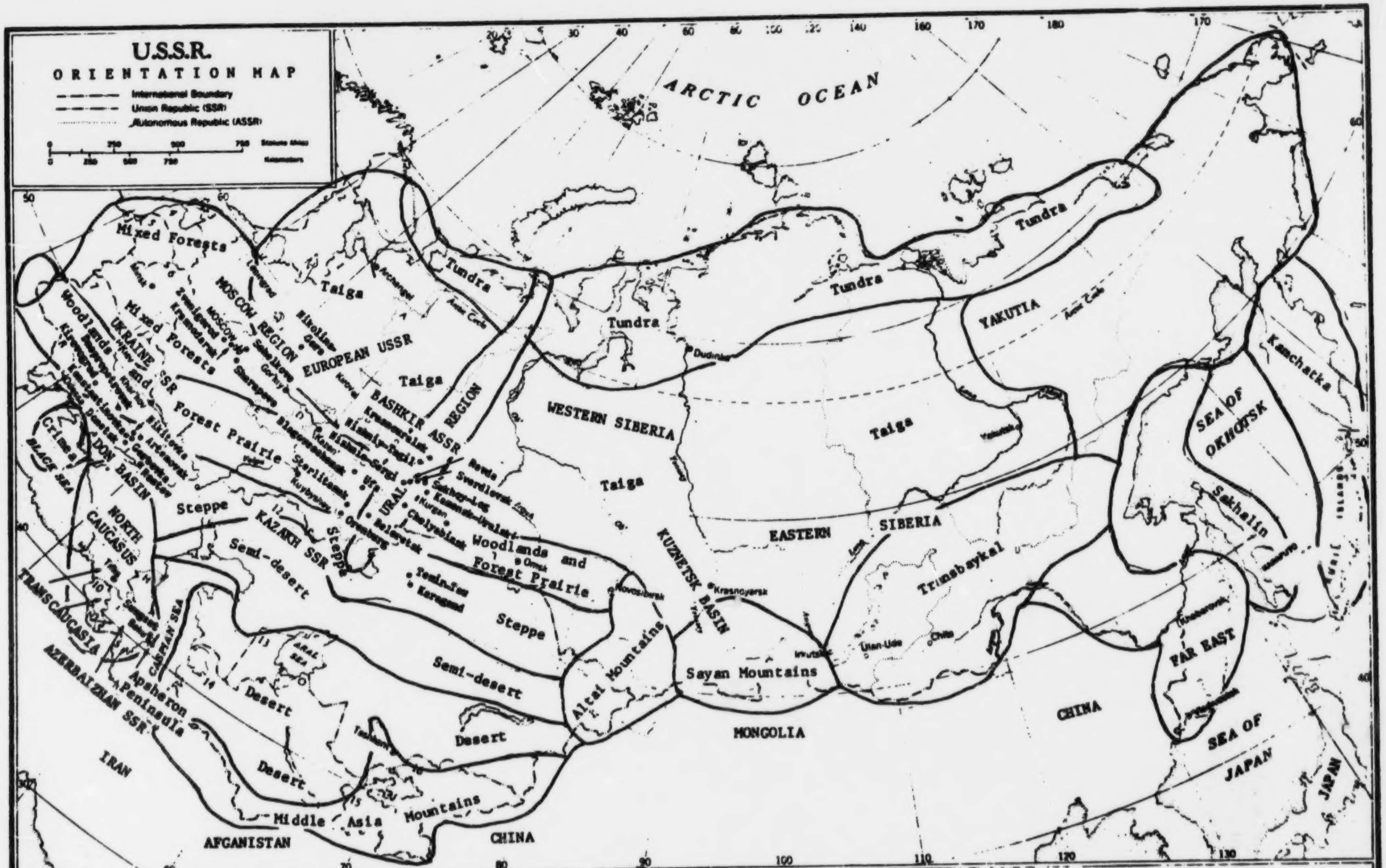
Some of the material presented here deals with various noxious pollutants emitted to the atmosphere in high concentration at or near ground level and with the exposure of these pollutants to the continuous mixing, diffusion, stirring, and dilution that takes place between regions of the atmosphere as a result of air turbulence. A number of papers deal with the intensity and structure of air turbulence in relation to temperature and wind, which form the background of atmospheric diffusion and stirring. Other papers deal with the direction frequencies and intensities of wind, which differ markedly for stable and unstable conditions of atmosphere; with the extremely slow diffusion through an inversion; and with the general climatology of atmospheric turbulence, diffusion, and the dispersions of air pollutants in different parts of the country and during different seasons of the year.

It must be borne in mind that the data presented in this volume relate to many diverse environments in a vast land area; that the USSR extends for about 7,000 miles from west to east and 3,000 miles from north to south; and that the country covers a wide range of climatic and relief conditions throughout much of its north-south and west-east extent. In this connection, a brief outline of the very general natural features of the USSR may be desirable. Lowlands and plains dominate the landscape of the major portion of the country. Its landscape can be roughly described as one consisting of broad latitudinal climatic belts of the lowlands and plains and of narrow, vertical climate zones of the highlands and mountains. Each of the broad latitudinal belts is distinct from the other in the major features of its climate, vegetation, and soils, though within each latitudinal belt there is a decrease in the annual precipitation as one proceeds from west to east. The latitudinal belts include the nearly barren and treeless tundra in the extreme north, where the winters are severe, the summers, short and cool, and where precipitation is very limited. There follow the belts of the taiga or coniferous forests, mixed forests, woodlands, forest prairie or forest steppe, the steppe, and the semi-desert. Finally in the extreme south, east of the Caspian Sea, there are the dry deserts, hot in summer and cold in winter, and, along the southern reaches of the Black Sea in Transcaucasia, there is a relatively limited area, humid and more or less subtropical, which is subject to mild winters, hot summers, and heavy precipitation.

It is hoped that the papers selected for presentation in this volume will permit an assessment of some of the USSR studies of the meteorological and topographic aspects of air pollution. As the editor of this volume I wish to thank my co-workers in the Air Pollution Section of the Institute for their valuable assistance.

M. Y. Nuttonson

Silver Spring, Maryland
November 1970



U.S.S.R.
ORIENTATION MAP

International Boundary
Union Republic (SSR)
Autonomous Republic (ASSR)
0
250
500
750
Statute Miles
Kilometers
ARCTIC OCEAN
Mixed Forests
Taiga
Tundra
MOSCOW REGION
MOSCOW
EUROPEAN USSR
Leningrad
Archangel
Arctic Circle
UKRAINE SSR
Mixed Forests
Woodlands and Forest Prairie
Gorkiy
Kirov
BASHKIR ASSR
URAL REGION
Sverdlovsk
Chelyabinsk
Magnitogorsk
Orenburg
Kuybyshev
Sterlitamak
Ufa
Kazan'
Kharkov
Kiev
Zaporozh'ye
Rostov
Crimea
BLACK SEA
DON BASIN
NORTH CAUCASUS
TRANSCAUCASIA
AZERBAIDZHAN SSR
Apsheron Peninsula
CASPIAN SEA
ARAL SEA
Steppe
KAZAKH SSR
Semi-desert
Desert
Middle Asia Mountains
Tashkent
AFGANISTAN
IRAN
CHINA
Woodlands and Forest Prairie
Omsk
Novosibirsk
Karaganda
WESTERN SIBERIA
Taiga
Dudinka
KUZNETSK BASIN
Krasnoyarsk
Altai Mountains
Sayan Mountains
MONGOLIA
EASTERN SIBERIA
Irkutsk
Ulan-Ude
Chita
Transbaykal
YAKUTIA
Yakutsk
Tundra
Kamchatka
SEA OF OKHOTSK
Sakhalin
FAR EAST
Khabarovsk
Vladivostok
SEA OF JAPAN
JAPAN
CHINA
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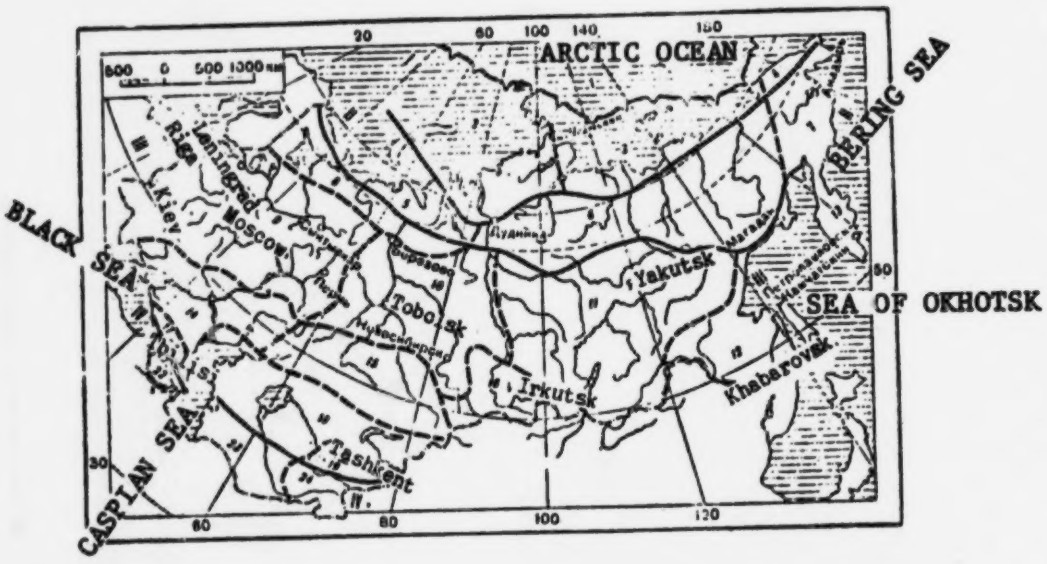
CLIMATIC ZONES AND REGIONS* OF THE USSR


ARCTIC OCEAN
BERING SEA
BLACK SEA
SEA OF OKHOTSK
CASPIAN SEA
Riga
Leningrad
Moscow
Kiev
Tobolsk
Yakutsk
Irkutsk
Khabarovsk
Tashkent
500 0 500 1000 km
20
60
100
140
180
80
120
50
30

Zones: I-arctic, II-subarctic, III-temperate, IV-subtropical
Regions: 1-polar, 2-Atlantic, 3-East Siberian, 4-Pacific, 5-Atlantic, 6-Siberian, 7-Pacific, 8-Atlantic-arctic, 9-Atlantic-continental forests, 10-continental forests West Siberian, 11-continental forests East Siberian, 12-monsoon forests, 13-Pacific forests, 14-Atlantic-continental steppe, 15-continental steppe West Siberian, 16-mountainous Altay and Sayan, 17-mountainous Northern Caucasus, 18-continental desert Central Asian, 19-mountainous Tyan-Shan, 20-western Transcaucasian, 21-eastern Transcaucasian, 22-mountainous Transcaucasian highlands, 23-desert south-Turanian, 24-mountainous Pamir-Alay

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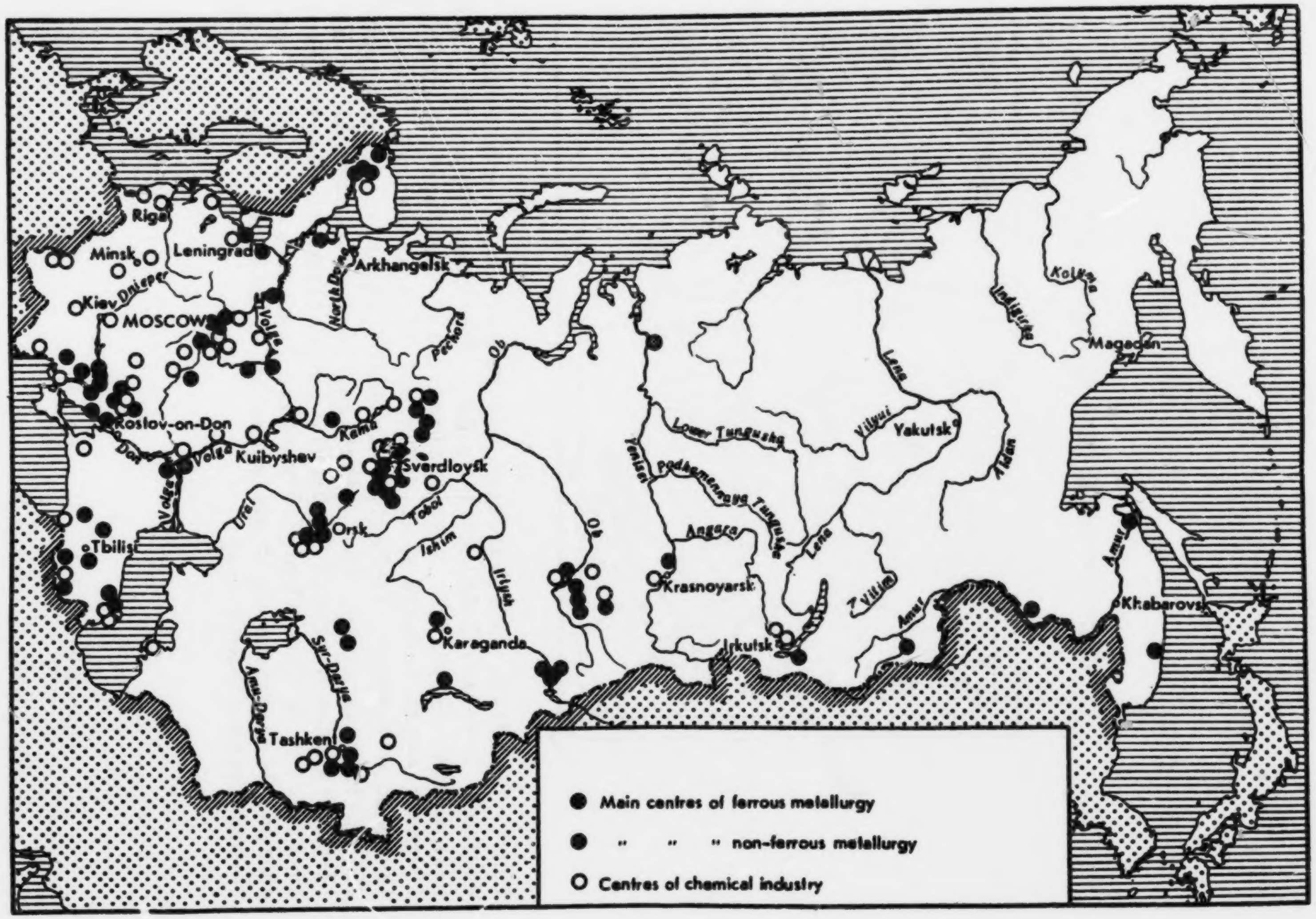
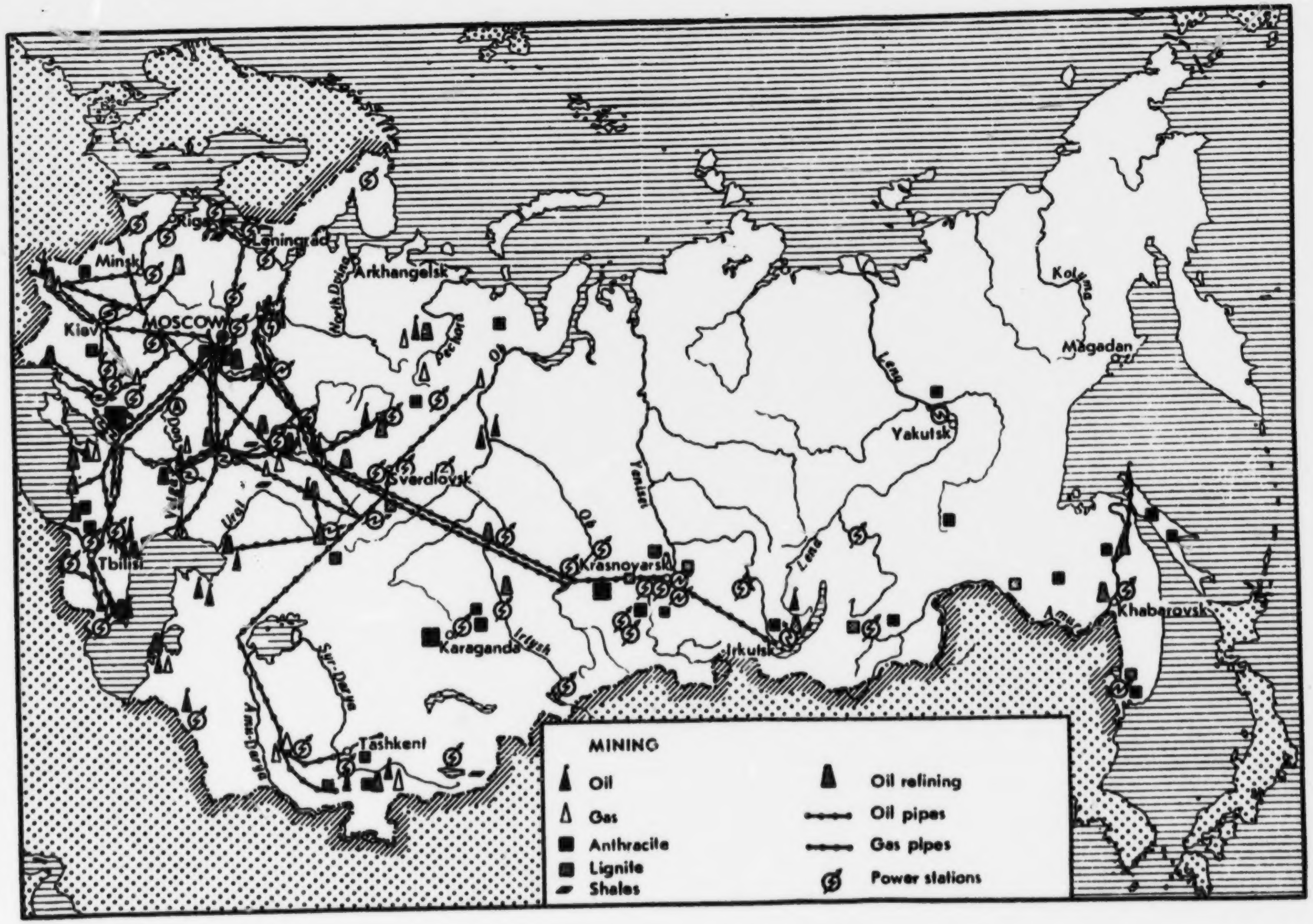
* After B. P. Alisov

THE MAJOR INDUSTRIAL CENTERS OF THE USSR


Riga
Minsk
Leningrad
Kiev
Dnieper
MOSCOW
Volga
North Dvina
Arkhangelsk
Pechora
Ob
Rostov-on-Don
Don
Kama
Kuibyshev
Volga
Sverdlovsk
Ural
Orsk
Tobol
Ishim
Irtysh
Tbilisi
Karaganda
Syr-Darya
Amu-Darya
Tashkent
Yenisei
Lower Tunguska
Podkamennaya Tunguska
Angara
Krasnoyarsk
Irkutsk
Lena
Vilyui
Yakutsk
Aldan
Vitim
Amur
Khabarovsk
Magadan
Kolyma
Indigirka
● Main centres of ferrous metallurgy
● " " " non-ferrous metallurgy
○ Centres of chemical industry

(After A. Efimov, "Soviet Industry", Moscow 1968)

THE MAIN MINING CENTERS OF THE USSR


Riga
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North Dvina
Kiev
MOSCOW
Pechora
Ob
Don
Volga
Ural
Sverdlovsk
Tbilisi
Yenisei
Lena
Kolyma
Magadan
Yakutsk
Krasnoyarsk
Irkutsk
Amur
Khabarovsk
Karaganda
Irtysh
Syr-Darya
Amu-Darya
Tashkent
MINING
Oil
Gas
Anthracite
Lignite
Shales
Oil refining
Oil pipes
Gas pipes
Power stations

(After A. Efimov, "Soviet Industry", Moscow 1968)

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STUDY OF POLLUTION OF CITY AIR BY INDUSTRIAL DISCHARGES

N. S. Burenin and B. B. Goroshko

__From__ Trudy, Glavnaya Geofiz. Observat. im. A. I. Voeykova, No. 238, p. 136-144, (1969)

Considerable attention is being given today to problems of study of atmospheric pollution by industrial discharges, i. e., this makes it possible to take specific steps toward improving the air reservoirs of cities. Particular importance is assumed by data on the chemical composition of air in cities, obtained from long-term collection and analysis of samples over a wide network of points located in different parts of a city. Such data permit the evaluation of pollution, account being taken of the dynamics of change as a function of the meteorological conditions determining the dispersal of impurities in the atmosphere. In addition, of considerable importance are single short-term surveys (lasting 1-1.5 months) with the organization of a large network of points for the collection and analysis of samples. They permit the establishment of the spatial distribution of noxious substances in the city air, the identification of areas of maximum and minimum pollution, etc.

A single survey of one of the major industrial and administrative centers of the Soviet Union was carried out in August-September 1968. The city extends over 25-30 km from north to south and about 20 km from west to east. It is situated in a hilly area where the elevations rise 50-70 m above the low points, and this under certain meteorological conditions may substantially affect the pollution of some of its sections. The air reservoir of the city is heavily polluted with a number of ingredients as a result of discharges of noxious substances from plants of the metallurgical, chemical, and machine-building industries located over the entire territory of the city. A major contribution to the pollution is made by automobile and especially by freight traffic. Based on incomplete data, 355 tons of dust, 274 tons of sulfur dioxide, and 470 tons of carbon monoxide are discharged daily into the air by the major sources.

According to the proposed standardization of cities [3] based on the principle of distribution of industrial enterprises, the city being surveyed may be classified as belonging to the second type, since the industrial enterprises that are the sources of pollution are scattered over its entire territory. For this reason, the adopted basis of the survey was the organization of a network of points where samples are collected two to three times a day. In all, 29 points were set up, each of which covered an average of 20 km^2. A number of factors (distribution of sources of discharge, local topography, etc.) were considered in the distribution of the collection points, particular attention being given to heavily polluted districts. For this reason, the density of the points in these parts of the city was higher and amounted to one point for 5-10 km^2, and on the outskirts of the city, it was correspondingly 3 to 4 times lower. The program of sample collection specified that data be obtained during the course of the entire daylight period (from 6 AM to 11 PM) in order to obtain the change of the concentration field, determinable by the meteorological conditions and by the variation of the volume of discharge. To supplement the sampling, the concentrations of noxious substances were determined at stationary points under the plume of the main source of discharge - a metallurgical complex - at distances of 0.5, 1, 2, 3, 5, 8, and 10 km from the center of the discharge. This made it possible to identify the zone of influence of noxious discharges from the complex, and the field of their possible maximum concentrations.

Considering the specific character of discharges from the industrial enterprises into the city's atmosphere, the collection and analysis of samples for the following ingredients were organized: dust, sulfur dioxide, nitrogen dioxide, carbon monoxide, phenol, sulfuric acid aerosol, chromium, manganese, and lead.

The meteorological observations were conducted at all points at a height of 1.5 m above ground. They included measurements of temperature and air humidity, wind velocity and direction, and the recording of particular weather phenomena. In addition, at the meteorological station located on the southwestern outskirts of the city, hourly gradient observations were made during the period of sampling to determine the air temperature and humidity and the wind velocity at levels of 0.5 and 2 m above ground, and the turbulence factor was calculated.

In order to characterize the pollution of the city's air basin from the data obtained, the main characteristics of air pollution were calculated according to districts and for the city as a whole: q_{av} - average concentration during the observation period, mg/m^2, g - frequency of concentrations above MPC, %, g_1 - the frequency of concentrations above 5 MPC, %; q max - the maximum concentration, mg/m^3, all listed in Table 1. The latter also gives the maximum concentrations encountered during the period of the survey.

It follows from Table 1 that the city's air is most heavily polluted with carbon monoxide, phenol, dust, and lead. Thus, the frequency of phenol and carbon monoxide concentrations above 5 MPC amounts to 43 and 26% respectively, and in some of its districts reaches 59 and 32%. In terms of excess of MPC for the city as a whole, g amounts to 86% for phenol and 83% for carbon monoxide, and in some districts this value is much higher. The maximum values also exceed many times the maximum permissible norms. The air reservoir of the city is polluted less with nitrogen dioxide and sulfur dioxide, but their maximum concentrations exceed MPC, and the frequency above MPC amounts to 45% for nitrogen dioxide and 4% for sulfur dioxide. Comparison of the degree of pollution of the atmosphere of individual city districts shows that the northern district is most heavily polluted with dust, nitrogen dioxide, carbon monoxide and lead, the central district with sulfur dioxide, carbon monoxide, sulfuric acid aerosol and phenol, and the southeastern district with dust, phenol, lead and carbon monoxide.

The presence of a large number of collection points made it possible to obtain not only a general pattern of the city's air pollution, but also a detailed spatial distribution of the concentrations of the noxious ingredients studied during the period of observations. Fig. 1 shows the concentration fields for dust, carbon monoxide, nitrogen dioxide, and sulfur dioxide. The schematic maps show isolines of equal concentrations. Analysis of the fields of concentrations on the territory of the city permits the identification of zones with high air pollution values. For example, it is evident (Fig. 1 a) that the isoline of the average dust concentration of 0.5 mg/m^3 surrounds almost all of the territory of the city, this being equal to the single maximum permissible norm, and over 3 times the mean daily maximum permissible norm. At the same time, in the northern and southeastern districts are seen areas with the most dangerous air pollution, where the concentrations considerably exceed even the single maximum permissible norms. These zones of maximum pollution are in accord with the location of the main dust-producing sources.

Table 1

Main Characteristics of Pollution of Air Reservoir with Industrial Discharges.

City District	Characteristic	Dust	Sulfur Dioxide	Nitrogen Dioxide	Carbon Monoxide	Sulfuric Acid	Phenol	Manganese	Lead	Chromium
Southwestern	q_{cp}	0,5	0,11	0,08	10	0,10	0,046	0,00065	0,0021	0,0001
	q_{max}	2,7	1,28	0,37	44	0,46	0,398	0,00135	0,0035	0,0003
	g	21	3	42	87	8	84	—	91	—
	g_1	1	0	0	22	0	25	—	0	—
Southeastern	q_{cp}	0,8	0,09	0,08	11	0,12	0,068	0,00130	0,0020	0,0001
	q_{max}	2,7	1,07	0,34	35	0,40	0,199	0,00260	0,0050	0,0006
	g	59	2	38	81	11	94	—	46	—
	g_1	1	0	0	28	0	59	—	2	—
Central	q_{cp}	0,5	0,13	0,07	12	0,17	0,057	0,00052	0,0012	0,0001
	q_{max}	2,4	1,80	0,33	36	0,57	0,353	0,00190	0,0030	0,0003
	g	25	8	37	88	29	92	—	13	—
	g_1	0	0	0	30	0	39	—	0	—
Northern	q_{cp}	0,7	0,11	0,09	12	0,08	0,048	0,00199	0,0015	0,0001
	q_{max}	3,5	1,20	0,60	61	0,46	0,222	0,00227	0,0070	0,0004
	g	49	4	41	77	6	83	—	68	—
	g_1	2	0	1	32	0	37	—	5	—
City as a Whole	q_{cp}	0,6	0,11	0,09	11	0,11	0,051	0,00110	0,0017	0,0001
	q_{max}	3,5	1,80	0,60	61	0,57	0,398	0,00260	0,0036	0,0006
	g	39	4	45	83	11	86	—	55	—
	g_1	1	0	0	26	0	43	—	2	—

The distribution of average carbon monoxide and nitrogen dioxide concentrations (Fig. 1 b and c) shows that the air reservoir is heavily polluted with these ingredients over the entire territory of the city. It must be noted that both in the first and in the second case, a large number of high concentration zones there are observed which are determined not only by the location of the major sources of atmospheric discharges, but also by the influence of discharges from motor transport. It was noted that the samples taken at points located near highways with heavy automobile traffic contained carbon monoxide and nitrogen dioxide in greater amounts than in other areas.

During the period of the studies, the air currents were directed predominantly from the site of the major sources of discharge of noxious substances toward the residential areas, where the major part of the sampling was carried out. For this reason, if special periods are excluded, the concentration values obtained in the city may be regarded as the maximum values.

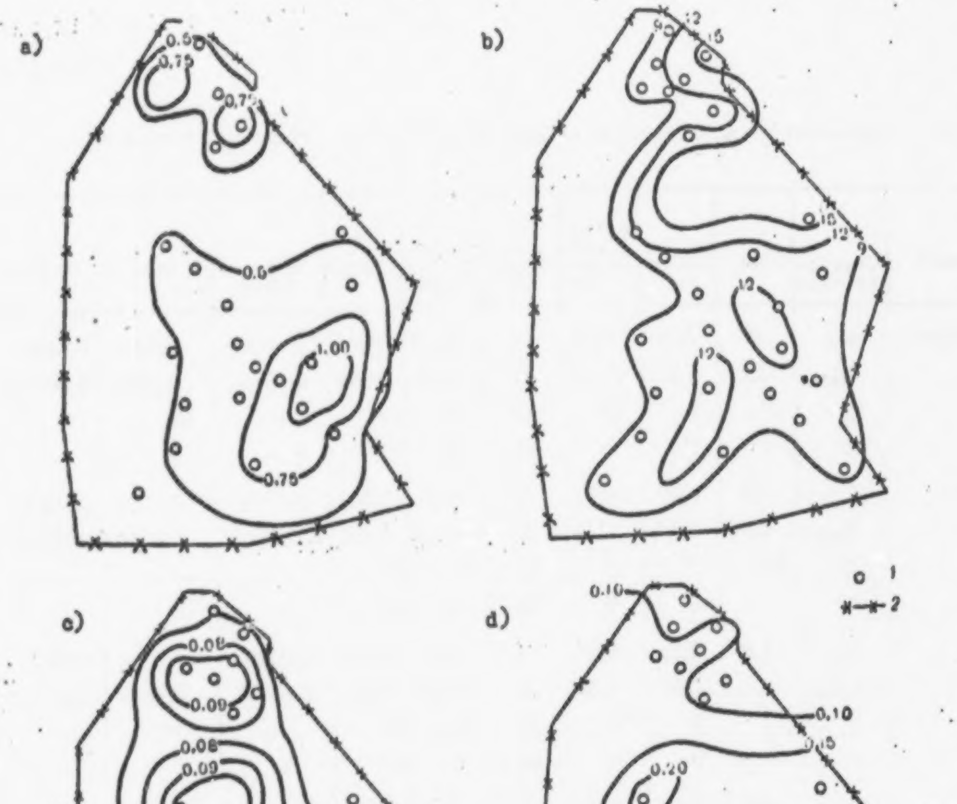

Fig. 1. Isolines of average concentrations of dust (a), carbon monoxide (b), nitrogen dioxide (c), and sulfur dioxide (d). 1 - points of measurement, 2 - city limit

It is of interest to consider the change of the concentration in a daily variation during the daytime. Two characteristic points were chosen for this purpose where repeated samplings of sulfur dioxide and nitrogen dioxide were carried out. The location of the collection points in relation to the industrial site of the major metallurgical complex varied. The first point (Fig. 2, curves 1, 2) was located at a distance of 150 m from the site, the second (Fig. 2, curves 3, 4) at a distance of 3.5 km. Curves 1, 3 correspond to the variation of average concentrations of sulfur dioxide, and curves 2, 4 -- to nitrogen dioxide. It is evident that the change of the concentrations is slight, but the curves have the opposite course. At the point located near the industrial site, maximum concentrations were observed in the mornings during a period of slight turbulent exchange. These concentrations are due to low and unorganized discharges.

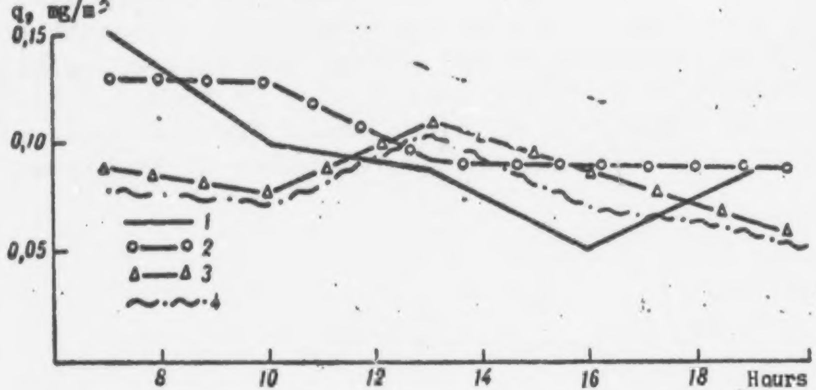

Fig. 2. Daily variation of concentrations of sulfur dioxide (1, 3) and nitrogen dioxide (2, 4) for two observation points in the city.

At the second point, located at a distance of 3.5 km, an increase in concentration is observed under daytime conditions. This indicates that the influence of primarily high discharges is manifested in this case. As turbulent exchange develops, mixing is intensified, and plumes from high sources, located at a height of 100-200 m, undergo a more vigorous dispersal. As a result, the concentrations near the ground increase [1, 2, 4, 7].

Samplings under the plume of the metallurgical complex at various distances show that the atmosphere in the range of influence of the plume is markedly polluted with different ingredients (Fig. 3). At the same time, two distinct maxima are observed for carbon monoxide, nitrogen dioxide and sulfur dioxide. The first is due mainly to unorganized discharges, and the second, at a distance of 3 km, to the discharge of noxious substances from high stacks.

The performed meteorological observations of the temperature and wind velocity and direction at the points of sampling made it possible to obtain a series of interesting data on the microclimatic characteristics of the territory of the city. It is known that the climate of a city differs substantially from that of the surrounding region. According to studies made by several authors [5, 6, 8, 9], this affects primarily the temperature regime and the distribution of the wind velocity and direction.

The temperature regime of a city is determined by the density of its construction, height of the buildings, distance between them, width of the streets and plazas, their arrangement with respect to the points of the compass, the vegetative cover, etc. A particularly strong temperature contrast with different parts of the city and the region surrounding it is provided by industrial sites, on the territory of which the air temperature is usually higher.

The formation on the territory of a city of areas with a higher air temperature, the so-called "heat islands," leads to the appearance of ascending currents of the type of stationary breezes over the city. This explains the formation of a cap of dense aerosol visible in clear weather above the city from afar [5]. On the other hand, the character of the wind in the city is affected by the fact that the buildings constitute a substantial obstacle to the air current. As a result, the movement of air before the city and within its confines slows down, so that an air cushion in the city is formed, which serves to lift the masses of air. Thus, the city increases the gustiness of the wind, decreases its velocity near the ground and increases it at higher levels.

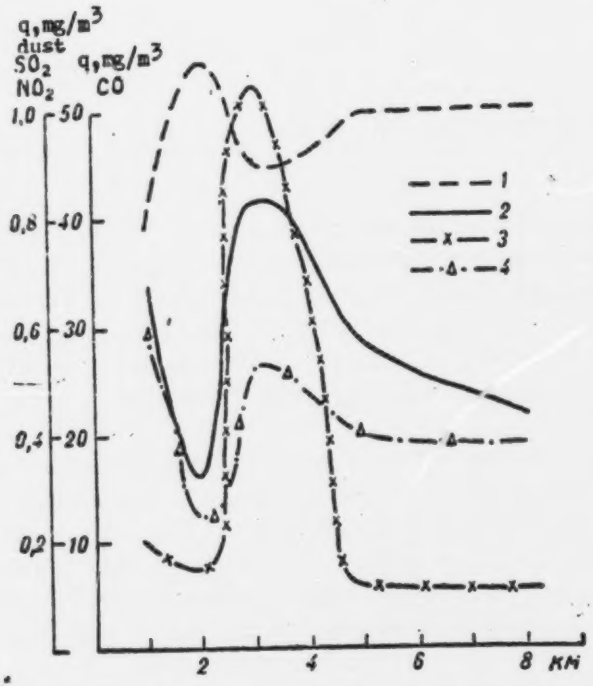

Fig. 3. Distribution of maximum concentrations in the area of the metallurgical complex.

1 - dust, 2 - CO_2, 3 - NO_2, 4 - SO_2

All these aspects of the distribution of microclimatic characteristics in a city are very important when analyzing the change of the degree of air pollution as a function of the meteorological conditions and in the subsequent forecasting of the occurrence of dangerous meteorological conditions (i. e., conditions under which the highest concentrations of noxious impurities in air are observed). Given below are some results of treatment of observational data on the wind direction for the northern area and the temperature and wind velocity for the entire territory of the city.

According to observational data on the wind direction at the surface of the ground during the course of the expedition, at 6 points of the northern area, a number of cases of wind direction were selected for 8 rhumbs for each point separately. Simultaneously, a selection of the wind directions based on data of the meteorological station was made for the same period of observations. On the basis of the data obtained, the frequency of directions for the eight rhumbs was calculated for the region as a whole, and is shown in Table 2. It follows from the table that the transformation of the air current under the urban conditions of the northern area has the following characteristics:

a) There is a sharp increase in the frequency of calm situations in the city due to the damping down of the wind velocities of all directions. For the area as a whole, the frequency of calms amounts to 17%, whereas according to the data of the meteorological station, it is equal to 2%. The greatest frequency of calms is observed at points located in the central part of the city.

b) The frequency of the wind direction for a number of rhumbs (northern, northeastern), based on the data of the meteorological station, decreases sharply as compared with the data obtained in the city. In the city, the frequency of the wind direction of eastern and western rhumbs increases.

Table 2

Frequency (%) of the Wind Direction Based on Data of Observations at the Meteorological Station and in the City

	Calm	NE	E	SE	S	SW	W	NW	N	
Based on data of meteorological station	2	24	9	4	1	5	9	21	25	
Based on data at points of sampling	17	0	17	0	1	2	27	22	14	

The conclusions reached are of major importance for calculating the atmospheric pollution of a city. The increase in the frequency of calm conditions in the city indicates that stagnation periods are more frequently observed here than can be determined from data of the weather station. The change of the wind direction under urban conditions also affects the pollution of certain areas. This becomes clear from an analysis of the factual material on atmospheric pollution. Data are frequently found which characterize a heavy pollution when the observation point during the sampling was not located under the plume of a large-capacity source, but at a distance of 0.5-2 km from the plume axis. A detailed examination reveals that although the plume is passing on the side, noxious substances which have reached the lower layer are transported along the streets in the direction of the air stream, which does not coincide with the main direction of the wind and can frequently be oriented at right angles to the main undisturbed stream. This causes pollution of territories that are not in the sphere of influence of the plume.

Thus, in comparing forecast warnings of meteorological conditions promoting the heaviest pollution of the northern area by discharges from the industrial enterprise located on the eastern border of the area, it is necessary also to consider the wind of the northeastern rhumb in addition to the wind of eastern direction.

According to data of meteorological measurements of the air temperature and wind velocity at 29 points of the city, such characteristics as the deviation of temperature at the point of sampling from the temperature at the weather station (ΔT) and the ratio of the wind velocity at the point of sampling to the wind velocity at the weather station (r_v) were calculated. From these characteristics, the fields of distribution of ΔT and r_v over the territory of the city were plotted (Fig. 4).

Analysis of the temperature field shows that almost over the entire territory of the city the air temperature was higher than outside the city. The average increase of the air temperature in the city during the period of observation is 0.4°. The main "heat island" is located in the southwestern area with a 1.2° drop of mean temperatures. This zone of high air temperature coincides with the industrial residential district having a railroad junction. In the central district one can also distinguish a high air temperature area that is adjacent along its northern boundary to the major industrial site. Furthermore, three zones can be distinguished where the air temperature is lower than outside the city: these are zones located in the river valley.

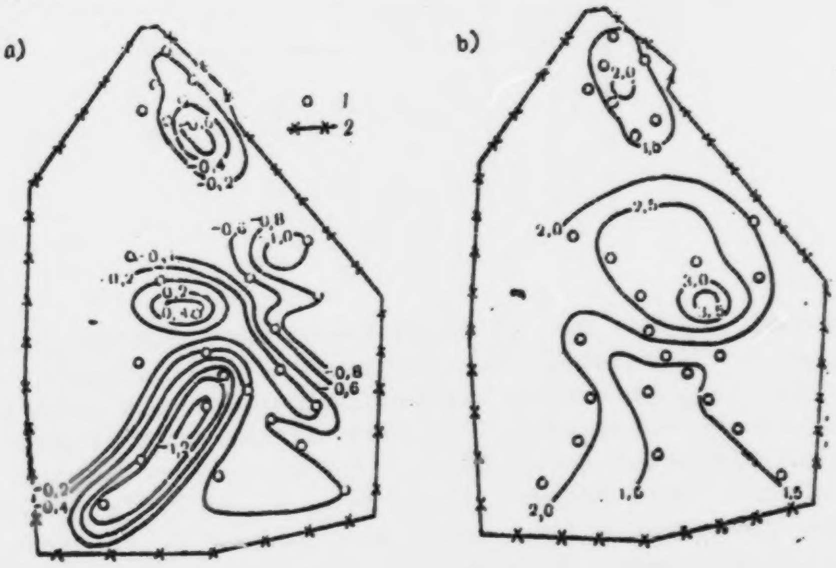

Fig. 4. Isolines of the distribution of ΔT (a) and r_v (b) on the territory of the city.
1 - points of measurement, 2 - city limit

As is evident from Fig. 4 b, the distribution of wind velocities in the city has its specific features. At almost all the observation points it was noted that the wind velocity in the city was 1.5-3.5 times less than outside it (at the weather station). The wind velocity decreases from the edge of the city towards the center. The zones of greatest air stagnation are observed in the central and northern areas. The maximum value of r_v is 3.5. The zones of greatest decrease of the wind velocity coincide with densely populated and built-up residential districts. As follows from the performed analysis of the degree of pollution of the air reservoir of the city, these are the two districts (central and northern) which are the most polluted.

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CHARACTERISTICS OF THE THERMAL REGIME OF CITIES

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In studying urban air pollution, it is highly important to know the characteristics of the urban meteorological regime. It is well known that the climate of a large city and that of its surroundings differ to some extent. These differences have been noted by many investigators on the basis of a comparison of data collected by weather stations located inside and outside the city limits. Such studies were made on the temperature and humidity of the air, velocity and direction of the wind, amount and nature of the precipitation, duration of fogs, solar radiance, etc. A fairly complete survey of completed studies, particularly those of German, British and French authors, is given in the book of P. A. Kratzer [6]. This can be supplemented with later studies of Soviet and foreign authors [2, 3, 5, 10, 21, 39 etc.]. These studies indicate that the mean annual air temperature in a city is 0.5-1.5°C higher than in its environs. The mean annual wind velocity in the city is 20-35% lower, the relative humidity of air is 5-10% lower, the frequency of fogs at the center of the city is higher, and the number of days with solar radiance is reduced [36]. In the city, a lag of the air temperature extremes and a decrease in the daily amplitude of the air temperature are observed.

A certain heating of urban air is attributed by the investigators to a change in the thermal balance resulting from the fact that the active surface in the city consists of materials of high heat capacity and thermal conduction [4, 33, 36, 40]. The pollution of atmospheric air, the heating of dwellings and the decrease ofthe wind velocity promote the retention of heat in the city, despite a decrease of solar radiation as compared to the surrounding area.

The insufficiency of weather stations makes impossible to obtain a complete picture of the temperature field of air in the city. Yet the knowledge of the horizontal and vertical distribution of urban temperatures is necessary for the solution of various problems. In particular, it is necessary for the study of the diffusion of impurities in the atmosphere. It follows from qualitative considerations that in certain types of weather, overheating of the city generates circulation in which the lines of flow are directed toward the center of maximum overheating [10, 40]. As a result, an industrial haze with very high concentrations of noxious impurities is formed over the city. However, these problems practically have not been studied from a quantitative standpoint.

Of late, the problems of temperature distribution in the ground layer of air in cities are being studied both abroad and in the USSR. A widely adopted method involves itinerary cruises around the city and its environs with more frequent temperature measurements at a height of 1.0-2.0 m above the active surface. It was found that isotherms superimposed on the plan of the city schematically duplicate the outline of the latter, with the overheating maximum coinciding with the most heavily built-up part of the city. In the literature, the phenomenon of overheating of city air has been termed "heat islands." In the last 15-20 years, similar investigations of a number of cities in Europe, the USA, Canada, and Japan have been carried out. In most of the published works, the conclusions are based on observations of an episodic character made in the course of several days at different times of the day and year, etc. Nevertheless, they have permitted the establishment of certain relationships in the distribution of urban air temperature. The most detailed investigations were made on the Swedish city of Uppsala [52], London [21], and some Japanese cities [33, 48, 50]. Since 1958, a special network of 58 meteorological points and 17 network stations have been set up in London [18].

Measurements of urban air temperatures have shown that heat islands are characteristic of almost all industrial cities, and that the temperature differences between the city and its environs vary from 1 to 10°C. The influence of a city on the air temperature depends on the weather conditions and some other factors. It increases in radiation-type weather (gentle wind and clear sky) and decreases with increasing wind and cloudiness. The diurnal variation of the difference in radiation-type weather has a maximum in the afternoon and particularly evening hours, since the city cools more slowly than its environs. For Japanese towns located on level ground, this difference does not exceed 3.0-3.5°C [48, 49, 50]. In London, with its typical urban layout, it reaches up to 4.5°C. For cities with a marked topography and a substantial air pollution, it increases to 7-10°C [28, 29, 47]. In the morning hours, for 1-2 hours after sunrise, the urban-rural temperature difference is minimum and may even take negative values, since the rural area heats up faster[39]. In advective type weather, the diurnal variation of the difference is manifested slightly, and the difference itself ranges from 1 to 2°C. For Tokyo, at a wind velocity of 6-8 m/sec, the difference is close to zero [23]. For cities located in the zone where two opposed wind directions predominate, the temperature difference depends substantially on the wind direction. Thus, in Baku [5] it may range from 5 to -2°C.

In the studies of Sundborg [52] and Kawamura [34], the least-squares method was used to derive formulas relating the nocturnal and diurnal change of the urban-rural temperature difference D_H to the cloudiness N, wind velocity u, temperature of the environs T and amount of water vapor e.

For nighttime hours, the Sundborg formula is

$$D_H = 2.8-0.10\ N-0.38\ u-0.02\ T + 0.03\ e.$$

It is interesting to note that the numerical coefficients for the Japanese cities and the Swedish city are approximately the same.

Analysis of the annual variation of the urban-rural air temperature difference shows that it is positive in practically all seasons of the year. The majority of the authors note that for European cities, the maximum values of the difference pertain to the summer period (Berlin [26], Prague [47], Krakow [51], etc.). In London [21] they may be observed in other seasons as well, in spring or autumn. In Saratov [2] this difference is smallest in summer because of the aridity of the surroundings as compared with a city with greenery. In Japanese cities, the maximum of the difference coincides with winter or spring. All the maximum seasonal values of the difference occur in the evening hours.

The effect of highest occurrence in the city during late evening hours was used by a number of authors for studying the heat islands of small cities [22, 30]. It was found that small cities whose population is 1/25 that of large cities have, under similar weather conditions and with an identical construction density, the same maximum urban-rural temperature difference as a large city. On this basis, Chandler [22] came to the conclusion that the intensity of a heat island is independent of the size of the city and hence independent of the size of the population. The opposite result was obtained by Mitchell [39]. He showed that during the preceding 60 years (1895-1954) the intensity of the heat island increased with the population in American cities. Fuqui [27] conducted similar investigations in 14 Japanese cities during the period from 1900 to 1940. The results obtained confirmed Mitchell's conclusion in reference only to cities with an initial population of over 200,000 people.

It is evident that the presence of a heat island in a city also generates a particular vertical distribution of temperature above the city.

Microclimatic observations made in different cities (Volgograd, Moscow, Göteborg, and Salzburg) showed some similar characteristics of the values of the temperature difference in the 0.5-1.5 m layer. They consist in the fact that over asphalt, which is the predominant cover in a city, the vertical temperature differences in the ground layer of 0.5-1.5 m have positive values in both summer [16] and winter [54] and vary from 0.1 to 1.0°C. In the diurnal variation in summer there is a maximum in the afternoon hours, when the difference ranges from 0.5 to 1.0°C. Early in the morning and in the evening, it decreases from 0.1 to 0.2°C. According to the observations in Göteborg, the maximum temperature difference above asphalt in the lower layer from 0.5 to 1.5 m fluctuates around 1°C in all months of the year.

Measurement of the air temperature above the city is a difficult problem, and such measurements have been few. In comparing the vertical temperature distribution in the city and its environs, Japanese investigators [34] carried out special measurements by means of resistance thermometers suspended from balloons up to heights of 30 m. In addition, they used the data from a 130-meter television tower in Tokyo. Data from television towers located in the city at the center of the heat island and also outside the city's zone of influence were studied for Canadian [41] and

American cities [19, 24]. One of the latest studies [19] reported for a vertical sounding of the atmosphere over New York and its environs by means of a helicopter.

Observations have shown that during the day, the temperature distribution over the city differs little from that over a village. Both in and around the city, superadiabatic lapse rates are observed. At night, the influence of the city is enhanced, and the heat island can be detected at heights 3 to 5 times greater than the height of the building [34]. During the cold period of the year, at night, the influence of the city is enhanced, and reduced during the warm period of the year. The height of the influence of warm urban air depends on its size. The larger the city, the greater the height to which urban air spreads. As was shown by the studies of DeMarrais [38], near-adiabatic lapse rates or moderate inversions predominate during the course of one year over the city at night. Superadiabatic gradients and large scale inversions are seldom observed.

A comparative analysis of inversions in nighttime was made in ref. [19]. It was shown that in most cases the ground inversions of the environs were associated with smaller urban inversions. Several elevated inversion layers were sometimes observed over the city. The average height of an elevated inversion was 300 m. The intensity of the heat island was maximum near the surface and decreased to zero at the height of 300 m. The maximum height of the "heat cap" in the city was 500 m. The "cross-over effect", in which the temperature under the heat island fell to values below the air temperature of the environs at the same level, was also observed in these studies.

Because of the rapid growth of cities, an increase in the volume of industrial production and the development of transportation, the problem of study of the influence of the city on the climate requires additional extensive investigations.

In connection with the study of the state of atmospheric pollution in July 1968, measurements were made on some meteorological characteristics of Donetsk, one of the major industrial cities of the Ukraine. The peculiarity of the area of observation lies in the fact that it is located on a dissected terrain where the heights are exceeded to a maximum of 100 m. The central, most densely built-up part of the city, coincides with high observation points. The combined influence of the natural and urban landscapes on the meteorological regime of the city has been studied insufficiently thus far and is of major interest.

To carry out the meteorological observations, 20 observation points were selected on the main territory of the city, taking into account the natural and urban features of the region studied, as much as possible in open spaces (squares, street intersections, banks of streams). The underlying surface of the urban points was predominantly asphalt, and that of the city's outskirts, soil or grass cover. The reference point selected was a weather station located on the outskirts of this city. Twelve urban observation points were referred to four elements of the city: low and high squares with a maximum height difference up to 80 m, the river embankment (lowest part of the city) and the streets. Seven suburban observation points were correspondingly referred to open squares, the highway and the river embankment.

At four points, including the weather station, the observations were stationary, and the remaining points were serviced by four automobiles with four observers. Each of the automobiles was assigned to a certain district of the city in such a way that the transit from one point to another, the setting up and unloading of the instruments, and the observations would last 30 minutes. At stationary points, the observations were made in the course of a 10 minute period every 30 minutes. At the same time, observations were made at four itinerary points. The points were toured according to a shuttle system. The measurements included the following elements. Suction psychrometers were used for observations of air temperature and humidity at heights of 0.5 and 1.5 m above the surface; the instruments were mounted on tripods in a horizontal position. Manual anemometers measured the wind velocity at heights of 0.5 and 2.0 m. A periodic mercury thermometer measured the surface temperature. The wind direction was recorded by means of a light pendant and a compass. At the weather station, the form and amount of cloudiness and at the remaining points, the condition of the sky (clear, variable, overcast) were determined. In addition, the state of humidity of the active surface was recorded.

From 19 to 22 June, two diurnal series (10 AM-2 PM), one morning series (6-9:30 AM) and one nocturnal series (11 PM-3 AM) were carried out. During this period, a typical anticyclonic weather prevailed. The wind velocity ranged mainly from 1.5 to 2.5 m/sec with a brief intensification during the day to 4-5 m/sec. The prevailing wind direction was southeastern.

Table 1

Values of Meteorological Parameters in the City and Suburbs (p) compared with the Reference Station (w) at Different Times of Day (mo - morning series, d - day, n - night).

Elements of City and Suburb	u_w/u_p		$\Delta T=T_w-T_p$ °C			$\Delta t_{0,5-2,0}$ °C			r %			$\Delta e=e_w-e_p$ mb		
	mc	d	n	mo	d	n	mo	d	n	mo	d	n	mo	d
Weather Station	1,0	1,0				—0,6	0,1	0,5	51	40	34			
High Open Spaces	1,7	1,5	—2,0	2,2	1,0	—0,6	0,3	0,7	43	42	32	0,7	0,2	0,9
Low Open Spaces	3,4	1,7	—1,8	1,6	0,9	0,0	0,0	0,6	48	52	36	—0,1	—1,5	0,2
City Enbankments	16,7	0,5	0,2	2,3	0,3	—	—	0,4	52	52	35	—1,7	1,8	0,4
City Streets	2,0	1,5	—1,2	0,3	0,1	0,0	0,1	0,5	50	41	31	—0,7	0,7	0,6
Suburban Streets	1,5	1,3	0,1	1,0	0,1	—0,3	0,0	0,8	54	46	34	—0,7	1,0	0,2
Suburban Highway	1,8	1,3	—2,1	1,1	—	—	0,0	0,5	47	46	—	0,9	—	—
Suburban Enbankments	1,8	0,7	3,7	2,7	0,5	—0,2	0,0	0,5	56	56	37	—2,1	2,9	0,5

The cloudiness varied from 0 points at night and in the mornings to 5-6 points Cu during the day. In the early morning, a light haze of industrial origin formed over the city. The results of the observations are found in Table 1 and Fig. 1. The table lists some meteorological parameters averaged for the period of the night (11 PM-3 AM) morning (6 AM-9:30 AM) and day (10 AM-2 PM) series. The number of cases of averaging is not uniform, depends on the duration of the series and the number of observation points, and varies from 4 to 19. The total number of readings for each element is 230. The table includes the following parameters: ratio of the wind velocity values at the weather station (u_w) to the wind velocity at the observation point (u_p) for a height of 2 m, air temperature difference Δ T°C. at a height of 1.5 m between the weather station and the observation points, lapse rate ΔT°C. calculated for the standard layer of 0.5-2.0 m, relative humidity r%, and difference in water vapor pressure Δe mb between the weather station and the observation points. Let us examine each parameter individually.

The wind velocity at the weather station changed only slightly in the course of a day, but it changed differently in the city during the same time. At night, with a general slackening of turbulent exchange, the wind velocity in the city and at its outskirts was considerably lower than in the open area, and amounted to about 1 m/sec at most points, and sometimes less. This made it impossible to calculate the ratio u_w/u_s for the nighttime. At sunrise, the wind velocity in the city began to increase, the ratio of velocities from morning to daytime decreased, and even fell below unity near the water reservoirs (Table 1).

In the analysis of the temperature of the underlying surface, three differences were examined: weather station (grass) - city (asphalt), weather station - suburb (grass) and weather station - suburb (bare soil). As is evident from Fig. 1, the fluctuations of the temperature differences between the surface of the soil at the weather station and the surface of the soil or grass at the suburban points are fairly large, particularly during the day, and are random in character. At the same time, the temperature difference between the soil surface of the weather station and the asphalt surface changes from positive values at night to negative values during the day. There is a change of sign two hours after sunrise. During the day, the asphalt surface constantly remains cooler than the soil surface. The extreme values of the difference are 1° and 8°C at night and -1° and -13°C during the day.

The air temperature difference ΔT at a height of 1.5 m between the weather station (T_w) and the observation points (T_p) does not remain constant during the day (Table 1). In the morning hours, because of the presence of a mist over the city, the air temperature of the latter is lower than at the weather station, and the average temperature difference is 1.5°C. During the day, this difference decreases to almost zero, in the evening hours it changes sign, and at night it becomes negative. The warmest are the central, highest parts of the city. For the 0 hr 30 min period, the maximum temperature difference between the center of the city and suburbs is 7.3°C if the topography is taken into account, and 3.0°C if it is not. The

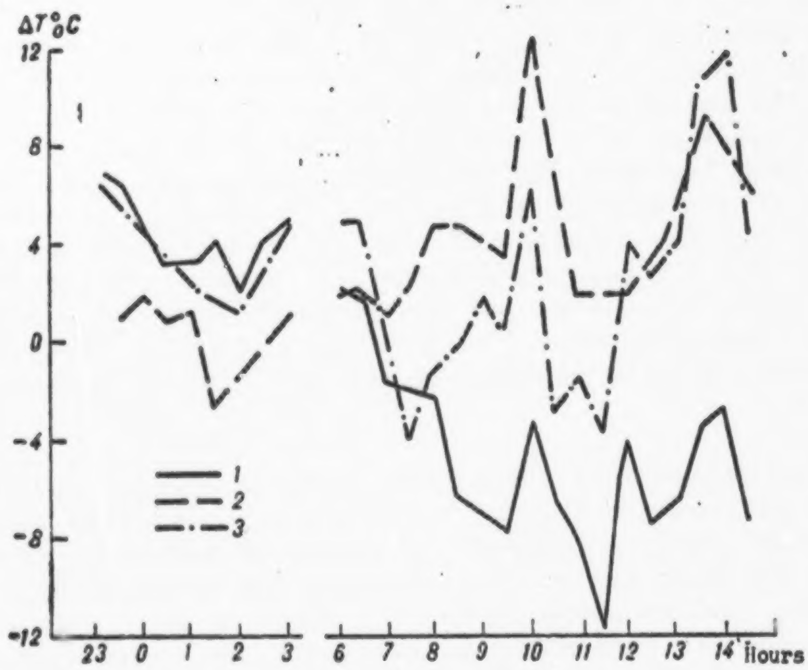

Figure 1. Surface Temperature Difference Between the Weather Station and The City, the Weather Bureau and the Suburbs.
1 - for asphalt, 2 - for soil, 3 - for grass

relatively high air temperature of the suburban highway is explained by the influence of two factors: the high location of the observation point and the presence of the asphalt strip. It is essential to note that the city embankment at night is warmer than the suburban embankments, whereas in the morning and during the day the differences between them are almost nonexistent.

The daily variation of the lapse rate Δtin the 0.5-2.0 m layer in the city is similar to that of the gradient at the weather station. Differences pertain only to the absolute values of Δt: during the day in the city and suburb, the lapse rate in the ground layer of air is slightly increased as compared with the lapse rate at the weather station (Table 1). In addition, attention is drawn to the lack of inversions at urban points in lower parts of the city.

The air humidity measured at a height of 1.5 m differs little in the city from the humidity at the weather station (Table 1). One can only note a certain decrease in air humidity over high open spaces and on city streets. A considerable amount of greenery in the city is a consequence of the slight humidity difference in the city and its environs.

The investigation has shown that in the city under study, a heat island is formed in the afternoon hours, and, as in other cities, manifests itself best during the hours of the night in the summertime. Thus, we should note an increased influence of the city on the thermal regime as a result of the action of two factors promoting an increase in the air temperature in the city during nighttime hours: an enhanced heat transfer in the central part of the city and a relative increase in the air temperature of this part of the city, as the one which is the most elevated.

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ANALYSIS OF METEOROLOGICAL CONDITIONS OF DANGEROUS AIR POLLUTION IN CITIES

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At the present time, in both theoretical and experimental studies [1-4 etc.], major attention is given to the investigation of the dispersal of noxious discharges from various industrial enterprises. It is obvious that a natural condition for the formation of high impurity concentrations in air is in this case the direction of the wind from the sources of discharges to the observation point. In the presence of this direction of the wind, the concentrations of noxious pollutants in the ground layer of air are determined by the wind velocity and the degree of turbulent exchange. In an extensive turbulent exchange, high impurity concentrations are created as a result of discharges from high smokestacks. Particularly unsafe conditions arise when a raised inversion takes place above the source of discharges [1, 2, 7].

In a city, because of the marked roughness of the underlying surface, an intensive turbulent exchange develops in the bottom layer of air, which may be reinforced as a result of the creation of the so-called "heat island" and breakdown of the lower part of the ground inversion [17, 22, 24, 25 etc.]. Other things being equal, the indicated effects obviously cause a substantial pollution of air by discharges from heavy industrial enterprises in the city as compared with the surrounding areas.

In principle, dangerous pollution of the atmosphere arising from the transport of discharges from the direction of the sources can be predicted. A synoptic forecast of the wind direction presents no difficulties. The possibility of forecasting the temperature profiles of the boundary layer on the basis of their relationship to synoptic situations has been demonstrated in earlier studies [8, 9, 12].

The characteristics of formation of high impurity concentrations in the city in the presence of stagnant air have been inadequately studied. Their analysis poses a whole series of questions, some of which are discussed in the present paper.

In order to predict a dangerous pollution of air, it is necessary to know the synoptic situations corresponding to the given phenomenon. There are indications that a marked air pollution is connected with anticyclones [10, 15, 16, 18, 20]. On the whole this is correct, but a more detailed analysis has shown that what is dangerous is not the anticyclonic circulation itself, but the gradientless pressure field frequently associated with it. From this standpoint, areas of pressure col and diffuse cyclonic fields are also in an unfavorable position. At the same time, a heavy air pollution does not have to arise at the periphery of the anticyclone.

In order to evaluate the influence of synoptic conditions and air pollution in a city, the following types of synoptic situations have been differentiated:

Type A. Gradientless pressure field. Such situations take place primarily in anticyclonic formations in the central portions of anticyclones, in extensions and ridges of high pressure, in nuclei, on the axes of crests, and also in pressure cols and in diffuse cyclonic fields. This type is characterized by calm or by a very weak wind. In the absence of substantial solar heat, it is associated with a stable stratification of the atmosphere, and usually ground inversions.

Type I. Intermediate field. This is observed in the presence of a directed pressure gradient. It is characterized by the location of the area studied between a cyclonic and an anticyclonic pressure formation or at the periphery of one of these formations. A stable preservation of wind of a certain direction is observed in this situation.

Type C. Cyclone. Characterized by cloudy weather, a reinforcement of wind, and precipitation. In a more detailed analysis, it is necessary to consider separately the front part of the cyclone, the warm sector, the rear and the cold northern part. Such details are not discussed in the present paper.

Considered below are synoptic situations in which a heavy and a relatively light air pollution are observed. The analysis makes use of data on several cities in which information on air pollution is relatively complete. In particular, the frequency of these types of synoptic situations is discussed for cases of heavy and light air pollution at three stationary points in the city of Magnitogorsk. In the calculations, use was made of selections based on data for daily concentrations of dust and sulfur dioxide in air for 1961-1964 given in [11]. Cases of simultaneous presence of several observations of high impurity concentrations (in no fewer than 4 samples out of 6, their values were higher than the MPC) and low concentrations at all points of the city were selected. The use of the above classification of synoptic situations for the analysis makes it possible to bring out the role of meteorological conditions in the creation of heavy air pollution (Table 1) much more distinctly than in past studies [10, 11]. In Table 1, $I_{n,e}$ is the intermediate field with transport of air from the north and east, and $I_{s,w}$ from the west and south. Such a subdivision of type I is related to the location of the main industrial enterprises in the northern, northeastern and western parts of the city; in the case of $I_{n,e}$, the impurities are carried to the residential sections of the city, where stationary observation points are located.

It is evident from Table 1 that the most characteristic situation promoting a heavy general air pollution over the city is the type A situation, i.e., a gradientless pressure field. This situation is observed in the great majority of days with a general air pollution. Its frequency in these cases is almost 5 times as high as on days with pure air. A second characteristic situation in which a heavy air pollution is observed is $I_{n,e}$, which is quite evident when its frequency in both groups of days is compared. This is determined by the characteristics of the transport of noxious impurities from the main industrial enterprises of the city. The steady wind of the western and southern quarters (situation type $I_{s,w}$) leads to the purification of air. The same result is produced by the passage of a cyclone. Obviously, from the standpoint of air pollution, situation A is dangerous because of the stagnation of air, and situation $I_{n,e}$, because of the transport of impurities from the sources of discharges to the residential areas of the city.

Table 1

Frequency (%) of Synoptic Situations on Days with Polluted and Relatively Pure Air in Magnitogorsk

Half-Year	Days	Synoptic Situations			
		A	$I_{n,e}$	$I_{s,w}$	C
Cold	With polluted air	66	23	9	2
	With clean air	13	3	69	15
Warm	With polluted air	64	27	7	2
	With clean air	14	3	58	28

Since a sufficient quantity of observations was available in Magnitogorsk, it was possible to set more rigid standards for the selection of cases of general air pollution over the city. It was possible to select days when out of 6 observations (3 tests for dust and 3 for sulfur dioxide) impurity concentrations above MPC were observed in no fewer than 5; at the same time, a fog was usually observed at the municipal weather station, a further indication of a heavy air pollution covering a considerable part of the city. Forty-two such days were selected. Of these, a gradientless pressure field was observed in 32 cases (76%). Thus, the danger of the type A situation was revealed even more definitely.

As an example, we shall consider one of the periods of heaviest general air pollution over Magnitogorsk, observed on 3-7 February 1963.

Fig. 1 gives a composite kinematic map for 3-7 February 1963, and Figs. 2 and 3, a ground level map and an AT_{700} map for 5 February 1963. It is evident from the figures that this period is characterized by the presence of a stationary anticyclone above the area considered. The pressure gradient was absent not only near the ground, but also at the H_{700} level (about 3 km). Consequently, a fairly thick layer with very weak winds should be observed. No wind was recorded on the surface on 3-7 February 1963. The air temperature ranged from -15 to -25°C., and a temperature rise took place only at the end of the period. Low temperatures combined with calm indicate the presence of a thick ground inversion [9, 12].

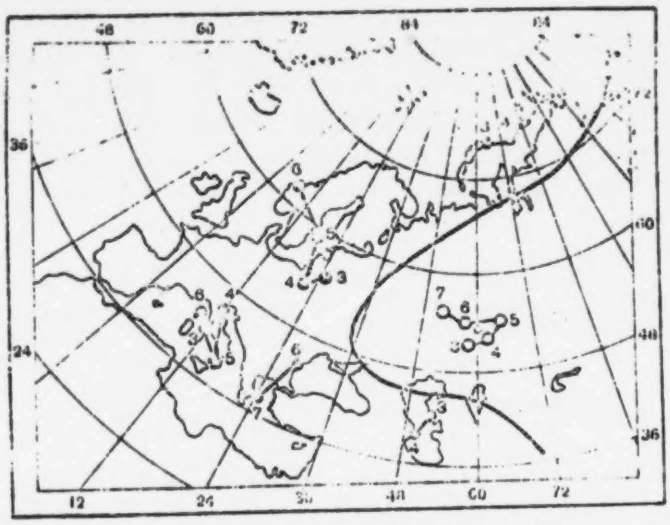

Fig. 1 Composite kinematic map for the period 3-7 February 1963.

All of the above characterizes the role of gradientless pressure fields in the creation of high impurity concentrations in cases of general air pollution in a city. It is obvious that if one considers the concentrations of impurities at individual points of the city, the frequency of the synoptic situations discussed earlier should be less, since in these cases one can observe local increases of concentrations that are not connected with the general air pollution in the city.

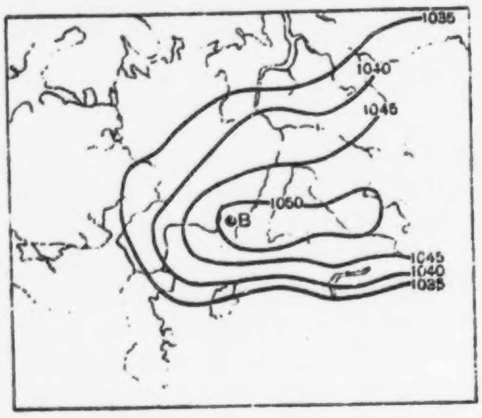

Fig. 2. Surface weather map for 3 A.M., February 5, 1963.

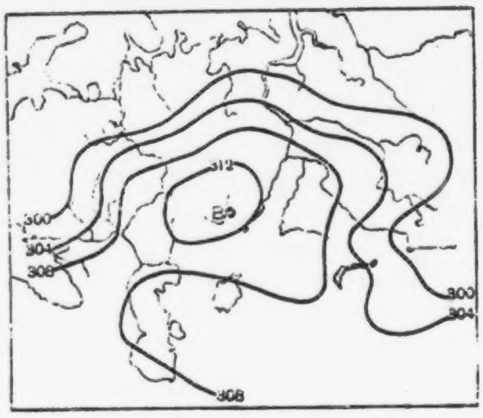

Fig. 3. Map of absolute topography of 700 mb surface for 3 A.M., February 5, 1963.

Synoptic analysis of cases of increased and decreased air pollution at various points of the city was based on data of 3 stationary points in Magnitogorsk (for dust and sulfur dioxide) and 5 stationary points in Rostov-on-Don. On the basis of data of each calendar month (1961-1964), 25% of the highest and 25% of the lowest values of the concentrations were selected. Synoptic situations corresponding to a high and low air pollution at various points of the city were considered for the cold (October-March) and warm (April-September) halves of the year. Table 2 shows the frequency of synoptic situations of types A and I.

As is evident from the table, during the cold half of the year, an increased air pollution in gradientless pressure fields is observed at each of the eight points considered in the two cities. The frequency of the type A situation ranges from 33 to 55%. However, 11 sets of observations (Table 2) definitely point to one regular pattern: the type A situation during the cold half of the year repeats itself 2 to 3 times more often at high impurity concentrations than at low ones. An increased air pollution in gradientless fields is not random, as can be readily demonstrated statistically, even if one does not consider the extent to which the frequencies of type A situations differ for cases of high and low impurity concentrations, and considers only the fact of high frequency, which took place in the type A situation in the presence of a high air pollution. It is obvious that if the indicated pattern did not exist, the theoretical probability P of an increase in the frequency of gradientless fields at high concentrations as compared to low ones would be ½. It is known that the probability p of random occurrence n of the events considered can be found from the formula

Table 2

Frequency (%) of Gradientless Pressure Fields (Type A) and Cyclones (Type C) for Heavy (1) and Light (2) Air Pollution at Various Points of Magnitogorsk and Rostov-on-Don

City	Impurity	Point	Cold Season				Warm Season			
			A		C		A		C	
			1	2	1	2	1	2	1	2
Magnitogorsk	Dust	1	43	13	5	13	57	42	6	12
		2	55	14	5	11	53	34	2	10
		3	47	15	4	12	56	35	3	14
		For all Points	48	14	4	12	56	37	4	12
	Sulphur Dioxide	1	40	12	6	16	53	38	5	9
		2	40	18	7	14	47	48	6	9
		3	35	12	8	12	56	45	2	9
		For all Points	38	14	7	14	52	43	4	9
Rostov-on-Don	Dust	1	44	24	4	7	60	47	0	0
		2	51	22	0	7	42	65	0	0
		3	33	22	0	5	51	48	0	0
		4	38	21	0	2	52	40	0	0
		5	41	24	0	24	64	57	5	0
		For all Points	42	23	1	7	53	51	1	0

$$p = P^n.$$

In the case under consideration, for $n = 11$ and $P = \frac{1}{2}$, $p \approx 0.05\%$.

Thus, the probability that the fact of increased air pollution in gradientless fields is not random in this analysis is 99.95%. During the warm half of the year, the heavier air pollution in gradientless fields shows up less distinctly. It is also apparent from Table 2 that mature cyclones promote the purification of urban air by removing the impurities.

The type C situation in the cities considered, particularly in Rostov-on-Don, occurs relatively seldom, but its frequency is invariably higher in the presence of light pollution than heavy pollution.

As follows from the above, the role of gradientless pressure fields in the creation of high impurity concentrations increases substantially when one considers cases of heavy air pollution at several points of the city simultaneously. This is evident from the above data and is illustrated by a comparison of Tables 1 and 2. This fact can be viewed in a new light by analyzing cases of high impurity concentrations on the basis of data from various stationary points of Magnitogorsk and Rostov-on-Don (Table 3).

Table 3

Frequency (%) of Gradientless Pressure Fields (Type A) in the Presence of Heavy Air Pollution

Impurity	High impurity concentrations during cold half of year no less than			High impurity concentrations during warm half of year no less than		
	At one Point	At two Points	At three Points	At one Point	At two Points	At three Points
				Magnitogorsk		
Dust	48	56	76	56	53	75
Sulfur dioxide	38	41	56	52	54	50
				Rostov-on-Don		
Dust	42	44	52	53	51	39

If one considers the heavier air pollution at various points without taking the values of impurity concentrations at other points of the city into account, the frequency of type A synoptic situations during the cold half of the year for Magnitogorsk is 48% for dust and 38% for sulfur dioxide, and for Rostov-on-Don, 42% for dust. These values are relatively high, particularly since, as is evident from Table 2, they are 2 to 3 times higher than the corresponding frequency for cases of light air pollution.

If cases of increased air pollution are considered at two points simultaneously (Table 3), the type A frequency increases by 3-8% based on three series of observations. In substantial simultaneous air pollution at all three points in the city, the frequency of the type A situation increases more substantially, by another 8-20% and reaches 52-76%. This pattern is observed by analyzing three independent series of observations.

During the warm half of the year, this pattern practically is not manifested, and the type A situation is not always characteristic of heavy air pollution.

Thus, gradientless fields are not associated with a local, but with a general increase of air pollution on the territory of the city.

It is characteristic that an increase in the concentration of impurities in stagnant air is observed in a number of cities of various countries [6, 15, 16, 17, 23, etc.]. This leads to the conclusion that the accumulation of noxious impurities in the city in this case takes place under different pollution conditions.

The possibility of creating a heavy air pollution under stagnant conditions as a result of high overheated discharges results from theoretical studies of M. Ye. Berlyand [4]. The surface concentrations of impurities from a source of fixed height are inversely proportional to the wind velocity. However, as the wind velocity decreases, the effective stack height H increases indefinitely, and the impurity concentrations decrease.

However, as was shown by M. Ye. Berlyand, under inversion conditions, for a rising stream, a ceiling of height z_n is created in the atmosphere, and the effective stack height H cannot increase indefinitely in the absence of wind. In this case, very high impurity concentrations may arise in the area of influence of discharges from heavy industrial enterprises. Particularly unsafe conditions are possible in the area of chemical-industrial enterprises with cold discharges.

The lack of high impurity concentrations in gradientless fields during the warm part of the year is owing to the fact that in summer no thick inversion layers are formed in the areas under consideration and, therefore, H may take very high values.

The very fact of increased pollution of city air under stagnant conditions, primarily in stationary anticyclones, when the given conditions persist for several days, may be considered established. A further step in the study of this problem is to determine the extent of danger of the stagnant situation in different seasons of the year, in different cities differing in the characteristics of discharges of noxious impurities into the air, the average level of air pollution, the relief, etc., and also in different parts of the same city. The first details of this problem are given below. The magnitude of air pollution with dust and sulfur dioxide under conditions of stationary anticyclones in Moscow, Leningrad and Magnitogorsk during the cold and warm halves of the year was compared with its average values. The frequency of impurity concentrations above the MPC was taken as the characteristic of air pollution. The results are given in Table 4.

It is apparent from Table 4 that the effect of increased pollution of city air in stationary anticyclones manifests itself in winter much more than in summer, and more for dust than for sulfur dioxide. Analysis of the data also shows that the higher the average level of air pollution (expressed quantitatively by the average frequency 9% of impurity concentrations above MPC), the greater the amount Δg by which this level is exceeded in stationary anticyclones. Thus, in Magnitogorsk, where the average level of air pollution during the period considered was high, Δg for dust reaches 34%. At the same time in Moscow, where the air is comparatively clean, Δg for

Table 4

Frequency (%) of Impurity Concentrations above MPC as an Average (g), During Periods of Stationary Anticyclones (g') and Difference Between these Values ($\Delta g = g' - g$)

Impurity	Part of Year	Moscow			Leningrad			Magnitogorsk		
		g	g'	Δg	g	g'	Δg	g	g'	Δg
Dust	Cold	10	17	7	21	33	12	39	73	34
	Warm	7	8	1	19	32	13	57	78	21
Sulfur dioxide	Cold	4	22	18	19	32	13	25	44	19
	Warm	9	7	-2	19	18	-1	29	33	4

dust amounts to 7% in winter and only 1% in summer. The correlation between g and Δg is fairly close, even if one considers the observational data for the cold and warm part of the year in combination (Fig. 4).

Thus, the stagnant conditions are more unsafe for a city with a high level of air pollution. If the air in the city is relatively clean on the average, stagnant conditions do not represent any particular danger.

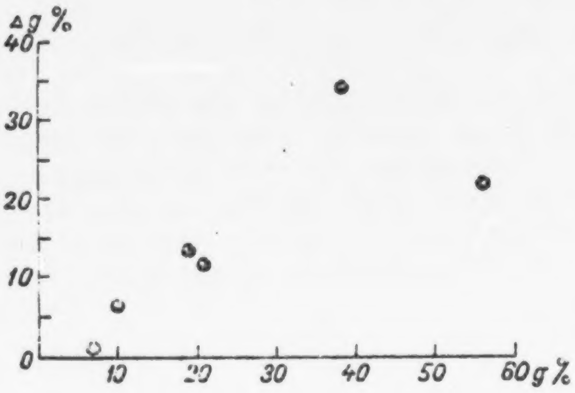

Fig. 4. Relationship between average value of frequency of dust concentration above MPC (g) and deviation from average under conditions of stationary anticyclones (Δg).

In order to adopt specific measures for decreasing air pollution when a stagnant situation occurs, it is necessary to know the extent of participation of various discharges in the creation of high impurity concentrations and certain other factors comprising the physical mechanism of the phenomenon studied. A solution of this problem requires special theoretical studies, but the analysis of the experimental material, whose results are shown in the present paper and in references [11, 12, 14, 15], permits a qualitative evaluation of some aspects of the problem.

High impurity concentrations are simultaneously observed at different points of the city. Thus, a heavy air pollution occurs over a considerable area. This indicates the relationship of the given process not only to discharges of specific sources but also to the general meteorological situation.

In the presence of a heavy air pollution over a considerable area of the city, in addition to the absence of wind near the ground, the winds are weak in a layer of the order of at least 1 km (there are indications that this layer amounts to 3-5 km [14, 16, 19]). It is obvious that in this case, the discharge of impurities from the upper part of the polluted layer of air over the city has been attenuated. At the same time, a certain reinforcement of turbulent exchange in a limited volume over the city as a result of the formation of a heat island, breakdown of the lower part of the surface inversion, and appearance of local air circulation [17, 22, 24, 25] causes the arrival of high discharges into the lower layer of air.

Impurities are washed out of city air with precipitation [11, etc.]. During a certain period of time after precipitation, the air is cleaner than before it. This indicates the presence of an impurity concentration outside the direct action of discharges, i.e., the creation of a background concentration in the city.

An increase in air pollution during stagnation is manifested primarily in the area where the pollution sources are located, and as the distance from them increases, the impurity concentrations decrease sharply.

The enumerated effects, established on the basis of an analysis of extensive experimental material, can be used for the physical solution of problems of propagation of impurities in city air under stagnant conditions. In addition, the results obtained are even now useful for the practical achievement of pure air in cities; in particular, they are and will be used for evaluating the state of air pollution on the territory of the Soviet Union.

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INFLUENCE OF THE RELIEF ON THE PROPAGATION OF IMPURITIES FROM SOURCES

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1. Studies of atmospheric diffusion of impurities pertain mostly to conditions of a comparatively level and horizontally homogeneous underlying surface. For these conditions, the basic regularities have been studied, working formulas have been derived, and practical recommendations have been made. The problem of the influence of the relief on the propagation of impurities has been studied to a considerably lesser extent. Moreover, under actual conditions, residential districts and industrial facilities discharging noxious substances are frequently laid out on rugged terrain. The roughness of the underlying surface causes a distortion of the structure of the airstream and hence may cause changes in the distribution of the concentration of impurities released by the sources.

A detailed analysis of these changes is very difficult at the present time, since it involves the solution of a problem that is complex in mathematical as well as physical terms. However, for the sake of a simplified study of the influence of the relief on the propagation of impurities, a series of simplifications may be introduced by using methods of solution of corresponding problems in the hydrodynamics and physics of the ground layer of air.

One of the first attempts to consider the influence of topographical irregularities in the calculation of the field of impurity concentrations was made in [1]. The present paper constitutes a development of this work. Like [1], the present study is based on a numerical solution of the equation of turbulent diffusion in an area with a curvilinear boundary. Considering that air currents in such a case are characterized by an inhomogeneous field of both the horizontal and vertical components of the wind velocity, u and w, this equation is written in the form

$$u\frac{\partial q}{\partial x} + w\frac{\partial q}{\partial z} = \frac{\partial}{\partial z} k_z \frac{\partial q}{\partial z} + k_y \frac{\partial^2 q}{\partial y^2}. \qquad (1)$$

Here q is the impurity concentration, and k_z and k_y are the vertical and horizontal components of the exchange coefficient. The x axis is oriented along the average wind, the y axis is perpendicular to it, and the z axis is oriented vertically upward. The boundary conditions used are: the absence of impurity flow on the underlying surface homogeneous in the direction of the y axis; a surface that, in the general case, is described by the function $z=h(x)$; the presence of a source at height $z=H$; and a decrease of the impurity concentration to zero at an infinite distance from the source.

According to [2], we can set $k_y = k_0 u$ and switch from a point source to a linear source, as is done for the conditions of a level area. Then

$$q = \frac{q'}{2\sqrt{\pi k_0 x}} e^{-\frac{y^2}{4k_0 x}}, \tag{2}$$

where q' satisfies the equation

$$u\frac{\partial q'}{\partial x} + w\frac{\partial q'}{\partial z} = \frac{\partial}{\partial z} k_z \frac{\partial q'}{\partial z} \tag{3}$$

and satisfies boundary conditions similar to the conditions for q

$$z' = z - h(x); \quad x' = x, \tag{4}$$

whereupon (3) changes into

$$u\frac{\partial q'}{\partial x'} + \left(w - u\frac{\partial h}{\partial x}\right)\frac{\partial q'}{\partial z'} = \frac{\partial}{\partial z'} k_z \frac{\partial q'}{\partial z'}, \tag{5}$$

where u, w and k_z are functions of the new variables x' and z'. The form of the boundary conditions remains unchanged.

To solve the formulated problem, one must know the distribution of displacement velocities and exchange coefficient for dissected topography conditions. However, the nature of the air currents under such conditions has been little studied, both in theory and in practice. It is, therefore, expedient to consider some simple models for the variation of u and k_z (w is determined from u from the continuity equation) for the purpose of an approximate study of the effect caused by the irregularities of the underlying surface. The form of equation (5) and of the boundary conditions after transformation (4) is the same as for the given problem in an area with a level ground surface. In a numerical solution of the problem with a computer, this makes it possible to utilize the program employed in [1, 4] for studying atmospheric diffusion above a horizontally homogeneous area.

In the case of a gently sloping relief, when the slope angles are small, the streamlines of the air currents are virtually parallel to the underlying surface. In this case, one can speak of a complete flow past the topographic irregularities. At the same time, the wind velocity and exchange coefficient are functions only of the height above the underlying surface: u = u[z-h(x)], k = k[z-h(x)]. On the basis of the continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial u} = 0 \tag{6}$$

we obtain

$$w = u\frac{\partial h}{dx}. \tag{7}$$

Equation (5) is now reduced to an ordinary diffusion equation for a level area in the absence of vertical displacement velocities. This means that in the case under consideration, the relief has no substantial effect on the propagation of the impurity. Hence it may also be concluded that a change of the concentration field under the influence of the relief is possible if u and k_z are functions not only of z' but also of x'. In this connection, the following relations were used in [1]:

$$\begin{aligned} u &= u_1(x)\,\widehat{u}\,[z - h(x)]; \\ k_z &= k_1(x)\,\widehat{k}\,[z - h(x)], \end{aligned} \tag{8}$$

where $u_1(x)$ and $k_1(x)$ are functions whose values are based on data of microclimatic observations.

However, on the basis of general considerations, such a model cannot be rigorous, since there must exist a boundary layer above which the influence of the relief on the wind velocity field is slight. This approach is suitable mainly for low sources, since model (8) leads to a distortion of the wind field at large heights. In the present study, an attempt is made to overcome these difficulties by two means. The first consists in replacing model (8) by another model that is physically more rigorous. The second means consists in analyzing the propagation of the impurity above an uneven underlying surface in a potential flow. As we know, a potential flow differs appreciably from a real flow, mainly near the underlying surface. It may be assumed, therefore, that it will be useful in analyzing the propagation of an impurity from high sources. The concluding part of the article points out a further development of the approaches discussed, which permits one to take into account both the influence of the ground layer of air and the characteristics of the attenuation of the influence of the relief at large heights.

2. In an approximate study of the velocity field of an air flow, use may be made of the fact that on the basis of experimental data, under conditions of gently sloping topographical features, the distribution of the wind velocity over the height in the ground layer of air is nearly logarithmic.

As an example, reference may be made to the results obtained in expeditionary studies of atmospheric pollution in the area of the Shchekino State Regional Electric Power Plant. These studies were made over the course of several years, in different seasons of the year, over rugged terrain with a height drop up to 50 m at a distance of 1 km. The gradient observations were made on a meteorological platform located on an elevation. Analysis of the measurements indicates, as was noted in [12], that the logarithmic law of change of the wind velocity and temperature with the height operates in this case. Microclimatic observations made at two points simultaneously, i. e., at the top of the hill and at its base, also showed that at both points the wind velocity profile was close to logarithmic.

On the basis of these assumptions, let us consider a hill of height h_0 (Fig. 1). In this case, the form of the underlying surface was described by the following relationship:

$$h(x)=\begin{cases} 0 \text{ for } x<d_1; \\ h_0\left[1-\left(\frac{x-d_1}{d_2-d_1}\right)^2\right]^2 \text{for } d_1\leqslant x<d_2; \\ h_0 \text{ for } d_2\leqslant x<d_3; \\ h_0\left[1-\left(\frac{x-d_3}{d_4-d_3}\right)^2\right]^2 \text{ for } d_3\leqslant x<d_4; \\ 0 \text{ for } d_4\leqslant x. \end{cases} \qquad (9)$$

The selection of formula (9) for h(x) insures the continuity of the derivative dh/dx at all points of the relief under study.

In accordance with the above-indicated considerations we shall assume that the wind velocity in the incoming flow is

$$u=u_{1_0}\frac{\log\frac{z}{z_0}}{\log\frac{z_1}{z_0}}, \qquad (10)$$

where u_{1_0} is the value of u at height z_1, and z_0 is the roughness of the underlying surface, which is assumed to be the same at all points of the relief. It is assumed that expression (10) also gives the wind velocity above the hill at $z>\delta_1(x)$ (Fig. 1).

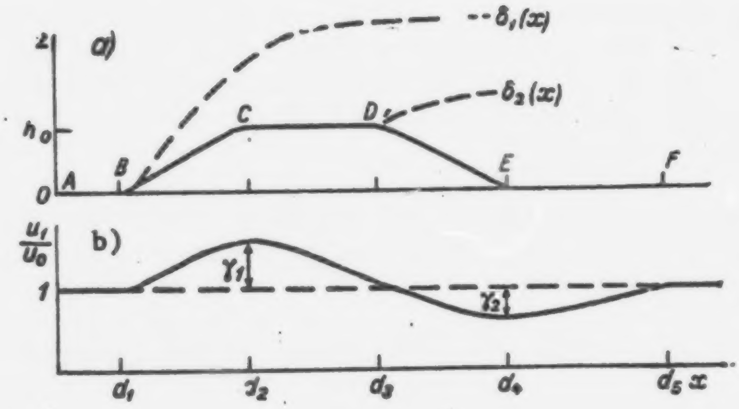
a)
z
$\delta_1(x)$
$\delta_2(x)$
h_0
0
A
B
C
D
E
F
b)
$\frac{u_1}{u_0}$
1
γ_1
γ_2
d_1
d_2
d_3
d_4
d_5
x

Fig. 1

On the windward slope C for $z<\delta_1(x)$ and on the leeward slope for $z<\delta_2(x)$ (Fig. 1), the change of the wind velocity is given by the following formula:

$$u=u_1(x)\frac{\log\frac{z-h(x)}{z_0}}{\log\frac{z_1}{z_0}},$$

where $u_1(x)$ is the value of u at height z_1.

On the leeward slope D for $\delta_2(x)<z<\delta_1(x)$, the wind velocity coincides with the velocity of the flow coming from the elevated part of the hill, i. e.,

$$u = \tilde{u}_1(x)\frac{\log\frac{z-h(x)}{z_0}}{\log\frac{z_1}{z_0}}, \tag{12}$$

where $\tilde{u}_1(x)$ can be determined from data on the damping of a disturbance in the air flow, assuming that the spread of the upper plateau is sufficiently great (in practice $\tilde{u}_1(x) \approx u_1|_{x=d_3}$). The equations for the determination of $\delta_1(x)$ and $\delta_2(x)$ are found from the condition of continuity of the wind velocity u at these levels:

$$u_1(x)\log\frac{\delta_1(x)-h(x)}{z_0} = u_{1_0}\log\frac{\delta_1(x)}{z_0};$$
$$u_1(x)\log\frac{\delta_2(x)-h(x)}{z_0} = \tilde{u}_1(x)\log\frac{\delta_2(x)-h_0}{z_0}. \tag{13}$$

Hence, δ_1 and δ_2 are expressed via the ratio of the function $u_1(x)$ to its value in the incoming flow. Usually, on the basis of microclimatic studies, the values of this ratio are determined for a height of 1 m at certain characteristic points of the relief [6]. Thus it is known that the wind velocity at the top of the hill is approximately 20-30% higher than on the level area. In the case under consideration, one can set $u_1(x) = u_1(1 + \gamma_1)$ for $\gamma_1 = 0.2\text{-}0.3$. At the foot of the leeward slope, the wind velocity is attenuated: $u_1(x) = u_1(1-\gamma_2)$ for $\gamma_2 = 0.2\text{-}0.5$. The values of $u_1(x)$ at other points of the relief are then described by an interpolation relation. To this end, it is convenient to use a third-degree polynomial, which provides for an adequate smoothness of the functions studied.

Recently, in order to obtain more complete characteristics of the wind velocities in a hilly area, studies involving simulation of air currents were performed in a wind tunnel [8].

With regard to the exchange coefficient in the incoming flow we shall assume that

$$k_z = \nu + k_{1_0}z \text{ for } z \leqslant h,$$
$$k_z = \nu + k_{1_0}h \text{ for } z \geqslant h, \tag{14}$$

where ν is the molecular viscosity of the air, h is the height of the ground layer of air, k_{1_0} being approximately proportional to u_{1_0}. As the wind velocity under hilly relief conditions changes, so does k_z. It may be approximately assumed that k_z under these conditions also increases in proportion to the height above the underlying surface and in proportion to the wind velocity, i. e.,

$$k_z = \nu + a u_1(x)[z - h(x)]. \tag{15}$$

Here $a = k_{1_0}/u_{1_0}$; since the exchange coefficient at a sufficient height should be independent of the relief, we shall assume that (15) is fulfilled for heights z at which $k_z < k_h$, and for large heights $k_z = k_h$.

Comparison of the calculations with the use of the given scheme for k_z and for the model according to which

$$\begin{aligned} k_z &= \nu + a u_1(x)[z - h(x)] && \text{for } z - h(x) \leqslant h; \\ k_z &= \nu + a_1 u_1(x) h && \text{for } z - h(x) > h \end{aligned}$$

shows that they yield approximately the same results. The vertical velocity w contained in (5) is determined from the continuity equation

$$w = -\int_0^z \frac{\partial u}{\partial x} dz. \tag{16}$$

Analysis of the formulated problem shows that if the slight influence of the molecular viscosity of air is neglected, the initial meteorological characteristics u_{1_0} and k_{1_0} enter into the functional dependence of the quantity $u_{1_0}q$ on the external parameters only, in the form of the ratio k_{1_0}/u_{1_0}. This enables one to reduce the volume of necessary calculations to some extent. This problem was solved numerically with an Ural-4 computer. Fig. 2 a, b and c shows examples of calculations of the distribution of the quantity s, proportional to the concentration q

$$s = \frac{2\sqrt{\pi k_0}}{Q} q(x, 0),$$

where Q is the capacity of the source. They were carried out for conditions of a hilly area whose outline is shown in Fig. 1 a. The following values were taken in the calculations: $h_0 = 50$ m; $d_{i+1} - d_i = 0.5$ km ($i = 1, 2, 3$); $d_5 - d_4 = 1.5$ km; $\gamma_1 = \gamma_2 = 0.2$; $u_{1_0} = 2$ m/sec; $k_{1_0} = 0.1$ m/sec; $\nu = 0.13 \times 10^{-4}$ m^2/sec.

The curves of Fig. 2 a, b, and c pertain to different positions of the source on the area and different heights of the source H. In particular, curves 1 and 4 pertain to cases where the source is located at the foot of the windward and leeward slopes, respectively, and curves 2 and 3, on the upper plateau of the hill on the windward and leeward slopes, respectively. Curve 5, which is given for comparison, pertains to the case of a level area. The calculations give the following values: H = 50 m (a); H = 150 m (b); and H = 400 m (c). It follows from the calculation that the relief has a substantial influence on the concentration field. The difference between the maximum values of the concentration as a function of the position of the source in the area amounts to 50% of H = 50 m. It diminishes with increasing source height and H = 200 m amounts to approximately 30%. It appears that

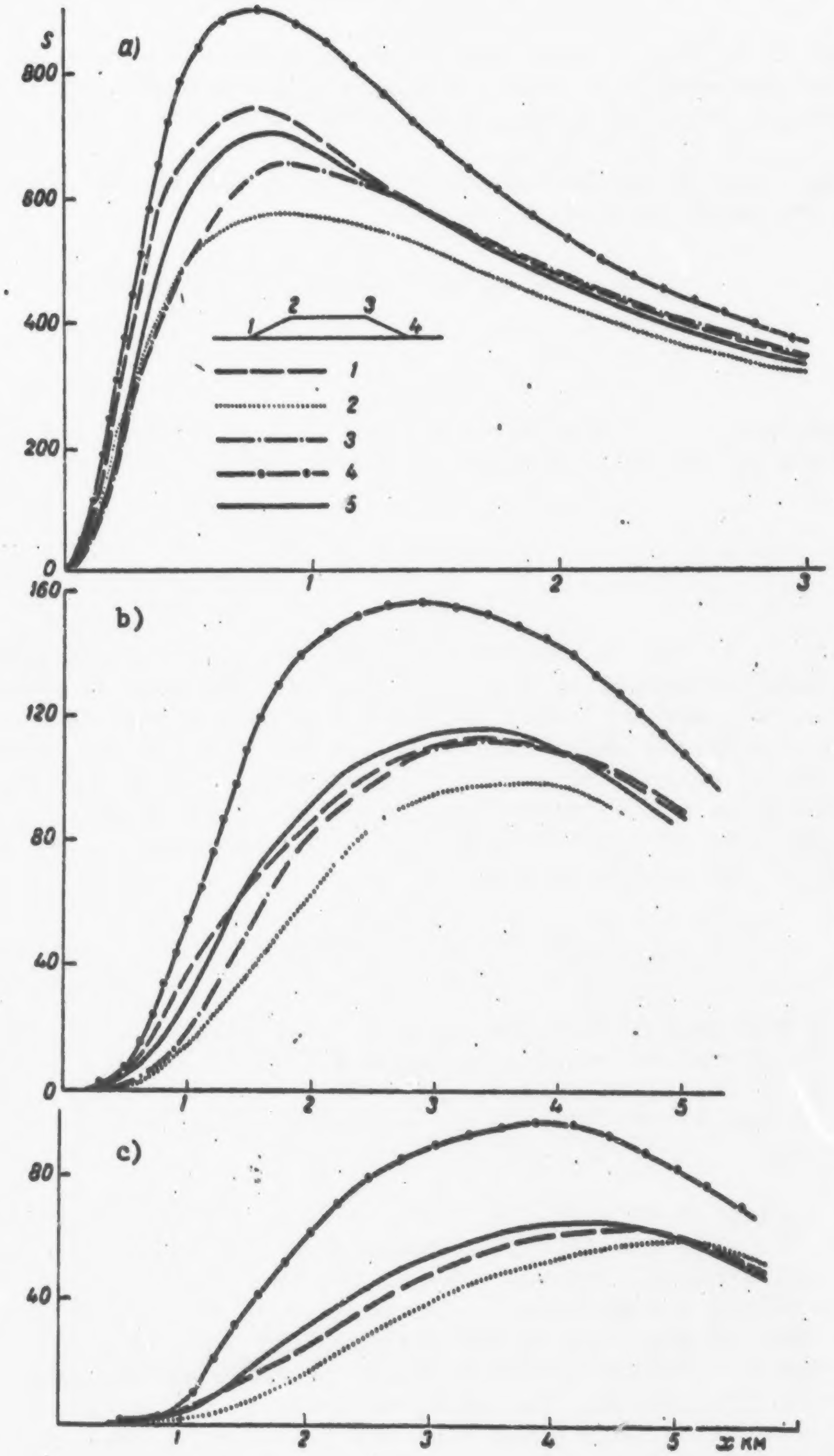
S
a)
800
600
400
200
0
1
2
3
1
2
3
4
1
2
3
4
5
160
b)
120
80
40
0
1
2
3
4
5
c)
80
40
1
2
3
4
5
x км

Fig. 2

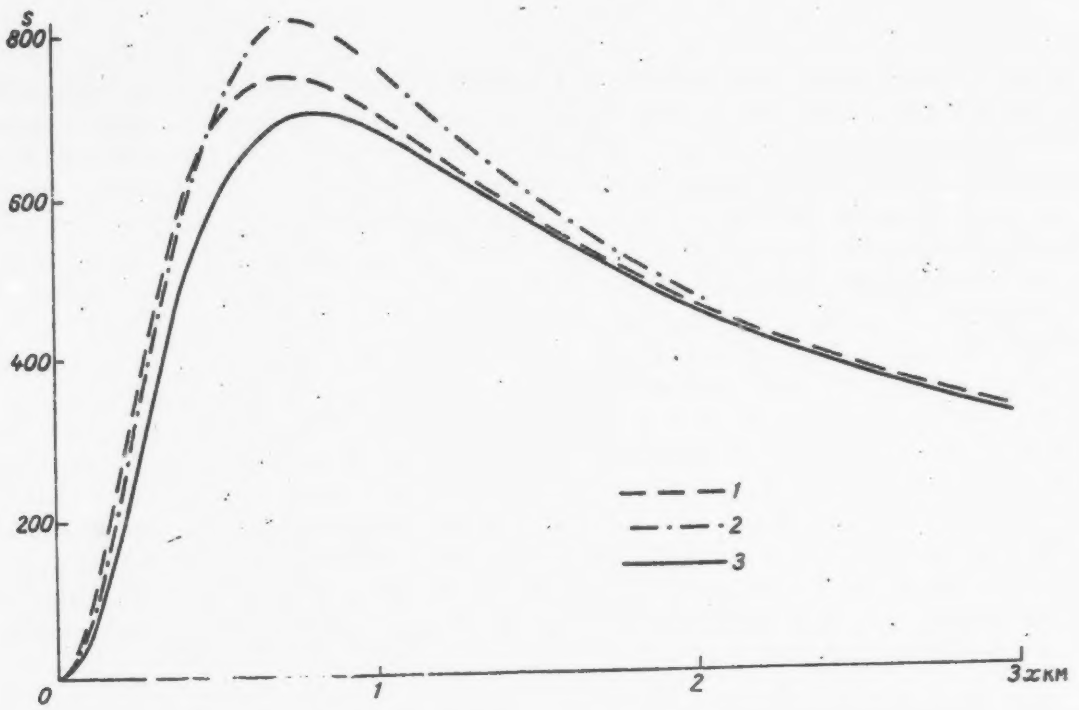

Fig. 3

such an influence of the source height may serve as a confirmation of the calculation scheme considered. The higher the location of the source on the windward slope, the lower the maximum concentrations. Conversely, the maximum concentrations increase more rapidly the closer the location of the source on the hill to the leeward slope and the lower its position on the leeward slope. The asymmetry of the influence of the leeward and windward slopes is manifested here. It is due to the fact that the wind is reinforced on the windward slope, and ascending currents arise which promote the upward transport of the impurity; whereas on the leeward side the wind becomes attenuated, and descending currents appear, which transport the impurity from the source downward.

When the source is located on the leeward slope, the concentration maximum is greater than on the level area, by approximately 30% for a stack height of H = 50 m and 20% for H = 200 m. Since the direction of the wind is variable and the windward slope may become leeward and vice versa, it must be concluded that the possible concentration maxima from a source of fixed height in a hilly area are usually higher than on level land.

The above examples pertained to a relatively rugged area with a height drop of only 50 m. As this drop and the steepness of the slopes increase, the influence of the relief is naturally enhanced.

As another characteristic example of an irregular topography, a scarp was considered. In this case, one can speak only of a single leeward (windward) slope. At a distance of 1.5-2 km from the windward slope, its influence is slight, and, therefore, the given case may be considered special as compared to the preceding case, assuming, for example, that the length of the elevated part in Fig. 1 is sufficiently large. Fig. 3 shows results of the calculation of the concentration when the source is located in front of the scarp in the presence of a wind toward the scarp (1), on an elevation in the presence of an opposite direction of the wind (2) and for a level area (3). It should be noted that the change in the concentration of the impurity from industrial sources located in a hilly area may also be caused by the influence of a change in the wind velocity and the initial ascent of the impurity above the stacks. Thus, on the leeward slope, where the wind velocity in the lower layer is attenuated, the relative increase of the wind velocity from the level of the wind vane to the level of relatively high stacks is greater than in the plain. Therefore, for the same wind velocity on the wind vane level, the initial ascent for stacks located on the leeward slope will be less, and hence the maximum of the ground concentration increases. According to the above results for a hilly area as well as for the conditions of a plain [3, 5], one can determine the value of the unsafe wind velocity at which the ground concentration reaches its highest values.

3. We shall now consider potential flows over the irregularities of the area. We shall use a known postulate of fluid mechanics, according to which the influence of the viscosity on the flow of a fluid is chiefly manifested in the boundary layer, which consists of a narrow region near the boundary of the underlying surface. In the remaining portion of space, the flow of the viscous fluid is close to inviscid, i. e., potential, flow. Moreover, it is noteworthy that in calculating the propagation of an impurity from a source, it is most important to assign correctly the coefficients in the equations of turbulent diffusion (1), (3) only in the region where the concentrations are high. Indeed, when potential flows are used in the problem under consideration, neglecting the influence of the boundary layer may affect its solution only in the region of relatively high ground concentrations. However, the condition of absence of impurity flow is assumed at the lower boundary, and hence for sufficiently high sources, the concentration gradients in this region are low. It may therefore be assumed that the errors in the assignment of coefficients in the region where the ground concentrations are close to maximum will have only a slight influence on the magnitude of this maximum. In addition,one should bear in mind that the definition of potential flow in a region with a curvilinear boundary amounts to finding a conformal map, which converts this region into a half-plane. The apparatus of the theory of functions of a complex variable used for this purpose is much simpler than that which is required even for an approximate solution of the problem of the flow of a viscous liquid.

An attempt to use the potential flow for solving problems of atmospheric diffusion was made recently by Stumke [16, 17]. The latter discussed equations of turbulent diffusion with constant values of the coefficients for the region with a piecewise linear boundary (of "searp" type), whose mapping on a half-plane is affected by a Christoffel-Schwarz integral. These interesting studies contain a number of useful results. However, the use of the

Christoffel-Schwarz formula, i. e., conformal mapping with a discontinuous boundary value of the derivative, has led the author to some physically unsubstantiated conclusions (for example, the appearance of infinitely high concentrations, etc.). The approach to the solution of the problem under consideration developed in the present paper permits the elimination of these drawbacks. It consists in the study of the equation of atmospheric diffusion with variable coefficients. Here the conformal mapping is effected by using functions that do not result in discontinuities of the flow velocities, etc.

To this end, the analytical function

$$\tau(t) = \varphi(x, z) + i\psi(x, z)$$

of the complex argument t = x + iz is introduced, which effects the conformal mapping of the region with the curvilinear boundary on the half-plane. It is usually termed a complex potential, its real part ϕ being the velocity potential and its imaginary part ψ being the stream function.

As we know (see for example [9] et al.), the horizontal and vertical components of the velocity of the potential flow in the region considered are then expressed by the formulas

$$u = \frac{\partial\varphi}{\partial x} = \frac{\partial\psi}{\partial z}; \qquad (17)$$

$$w = \frac{\partial\varphi}{\partial z} = -\frac{\partial\psi}{\partial x}.$$

The curves $\psi(x, z)$ = const represent streamlines of the flow studied. In particular, the line $\psi(x, z) = 0$ is the boundary of the region.

Equally complete information on the potential flow is contained by the reverse function

$$t(\tau) = x(\varphi, \psi) + iz(\varphi, \psi),$$

which effects the conformal mapping of the half-plane onto the physical region of flow.

If the components of the velocity field (17) are substituted into the equations of turbulent diffusion and, in addition, a definite model is taken for the exchange coefficient (for example, it is related to the wind velocity), the problems of interest to us can, generally speaking, be solved only numerically. However, a number of conclusions may be obtained analytically. To this end, in the diffusion equation it is necessary to switch from the variables (x, z) to the "flow" coordinates ϕ and ψ. If, in the equation obtained, the terms describing the diffusion transfer along the flow are neglected, as compared with the convective terms, and if one sets $k_x = k_z$, the turbulent diffusion equation (3) will take the form:

$$\frac{\partial q'}{\partial \varphi} = \frac{\partial}{\partial \psi} k_z \frac{\partial q'}{\partial \psi}. \tag{18}$$

The initial and boundary conditions can then be written in the form:

$$\begin{aligned} q' &= Q\delta(\psi - \psi_H) \quad \text{for } \varphi = \varphi_H; \\ k_z \frac{\partial q'}{\partial \psi} &= 0 \quad \text{for } \psi = 0; \\ q' &\to 0 \quad \text{for } \psi \to \infty. \end{aligned} \tag{19}$$

Here Q is the capacity of the source, ϕ_H, ψ_H are the flow coordinates of the source located at point $x = x_0$; $z = H + h(x)$, and $\psi = 0$ is the straight line into which the boundary $z = h(x)$ is converted upon mapping ; $\delta(\psi)$ is the delta function.

The equation obtained and the boundary conditions coincide in form with those which were used in the problem of atmospheric diffusion over a horizontally homogeneous surface.

If it is assumed for the exchange coefficient that $k_z = k_z(\psi)$, i. e., a model which is a natural generalization of those usually employed for k_z, the solution of the problem (18)-(19) may be written in the form

$$q' = q'(\varphi - \varphi_H, \psi, \psi_H). \tag{20}$$

As in the case of a horizontally inhomogeneous underlying surface (cf. [15]), the point ϕm, where the maximum of the ground concentration is reached, is determined from the condition $\frac{\partial q'}{\partial \phi} = 0$ for $\psi = 0$. It is evident from (20) that the following relations should hold:

$$\varphi_m - \varphi_H = f(\psi_H). \tag{21}$$

Substituting it into (20) we find that the maxiumum ground concentration q'_m depends solely on ψ_H, i. e.,

$$q'_m = q'_m(\psi_H). \tag{22}$$

In other words, for sources located on the same streamline, the maximum ground concentration is the same.

This conclusion is also valid for maximum ground concentrations from point sources, since it may be approximately assumed that a relation of the type of (20) applies to them as well.

In order to obtain the desired purity of the atmosphere, the source height H should be determined in such a way that the maximum ground concentration q_m is less than the maximum permissible value (q_m<MPC). Let us assume that above a horizontally homogeneous surface (or at a sufficient distance from the curvilinear portions of the boundary) this makes it necessary that the source have a height H_0. It then follows from the model considered that at finite distances, the requisite purity of the atmosphere is obtained by placing the sources on the streamline $\psi = \psi H_0$, where $\psi H_0 = \psi(\infty, H_0)$. In other words, ψH_0

is the value of function ψ on a streamline that, at an infinite distance from the curvilinear portions of the boundary, is located at distance H_0 from the underlying surface.

At the same time, at finite distances, the necessary geometrical source height H is the distance from the streamline $\psi = \psi H_0$ to the underlying surface

$$H = z(\varphi_H, \psi_{H_0}) - z(\varphi_H, 0). \tag{23}$$

This expression may be rewritten in the form

$$H = H_0 r(H_0, \varphi_H), \tag{24}$$

where r (H_0, ϕ_H) is a correction factor dependent on the position of the source relative to the relief and to the source height H_0.

The form of the function $r(H_0, \phi_H)$ is completely defined by the geometry of the flow in the region considered. After some slight changes, the above results may also be obtained for the model

$$k_z = f_1(\varphi) f_2(\psi).$$

Let us now consider the conformal mapping of the half plane onto a region with a boundary close to the one shown in Fig. 1. To do so we shall make use of the fact that the Zhukovskiy function $t = \frac{1}{2}\left(s + \frac{a^2}{s}\right)$ effects the mapping onto the half-plane of a region whose boundary is made up of a real axis and of a semicircle of radius α with its center at the origin of coordinates. The semiellipse whose minor semiaxis coincides with the $(-\alpha, \alpha)$ segment of the real axis is then converted on the plane into a curve having a zero angle of entry into the real axis. Combining Zhukovskiy's map with the map $s = \sigma + m\sqrt{\sigma^2 - a^2}$, which converts the half-plane into the region bounded by the real axis and the semiellipse with semiaxes a and ma, we find the desired map in the form

$$t = \frac{1}{2}\left[\sigma + m\sqrt{\sigma^2 - a^2} + a^2\left(\sigma + m\sqrt{\sigma^2 - a^2}\right)^{-1}\right], \tag{25}$$

here

$$t = x + iz; \quad \sigma = \xi + i\zeta; \quad m = \frac{h_0}{a} + \sqrt{\left(\frac{h_0}{a}\right)^2 + 1},$$

where h_0 is the height of the hill and a is its half-width. The branch of the root is fixed by the condition $\operatorname{Im}\sqrt{\sigma^2 - a^2} \geqslant 0$ for $\operatorname{Im}\sigma \geqslant 0$.

Using (25), one can construct the potential flow whose complex potential is given by the relation

$$\tau = A\sigma, \tag{26}$$

constant A being determined from the requirement that at an infinite distance from the obstacle (i. e., in the incoming flow), the velocity of the potential flow be equal to v. Hence

$$A = \frac{1}{2} v (1 + m). \tag{27}$$

Separating the real part from the imaginary part in (25) and setting $\zeta = 0$, we obtain a parametric equation of the boundary of the region for which the potential flow was constructed:

$$\text{for } |\xi| \leqslant a: \quad x = \frac{1}{2} \xi \left[1 + \frac{a^2}{\xi^2 + m^2 (a^2 - \xi^2)} \right]; \tag{28}$$

$$z = \frac{1}{2} m \sqrt{a_z - \xi^2} \left[1 - \frac{a^2}{\xi^2 + m^2 (a^2 - \xi^2)} \right];$$

$$\text{for } |\xi| > a: \quad x = \frac{1}{2} \operatorname{sign} \xi \left[|\xi| + m \sqrt{\xi^2 - a^2} + a^2 \left(|\xi| + m \sqrt{\xi^2 - a^2} \right)^{-1} \right];$$

$$z = 0.$$

It can be readily seen that the function z = h(x) determinable from (28) has a continuous first derivative, so that the region of flow is sufficiently smooth. The velocity components obtained from (17) undergo no discontinuity anywhere.

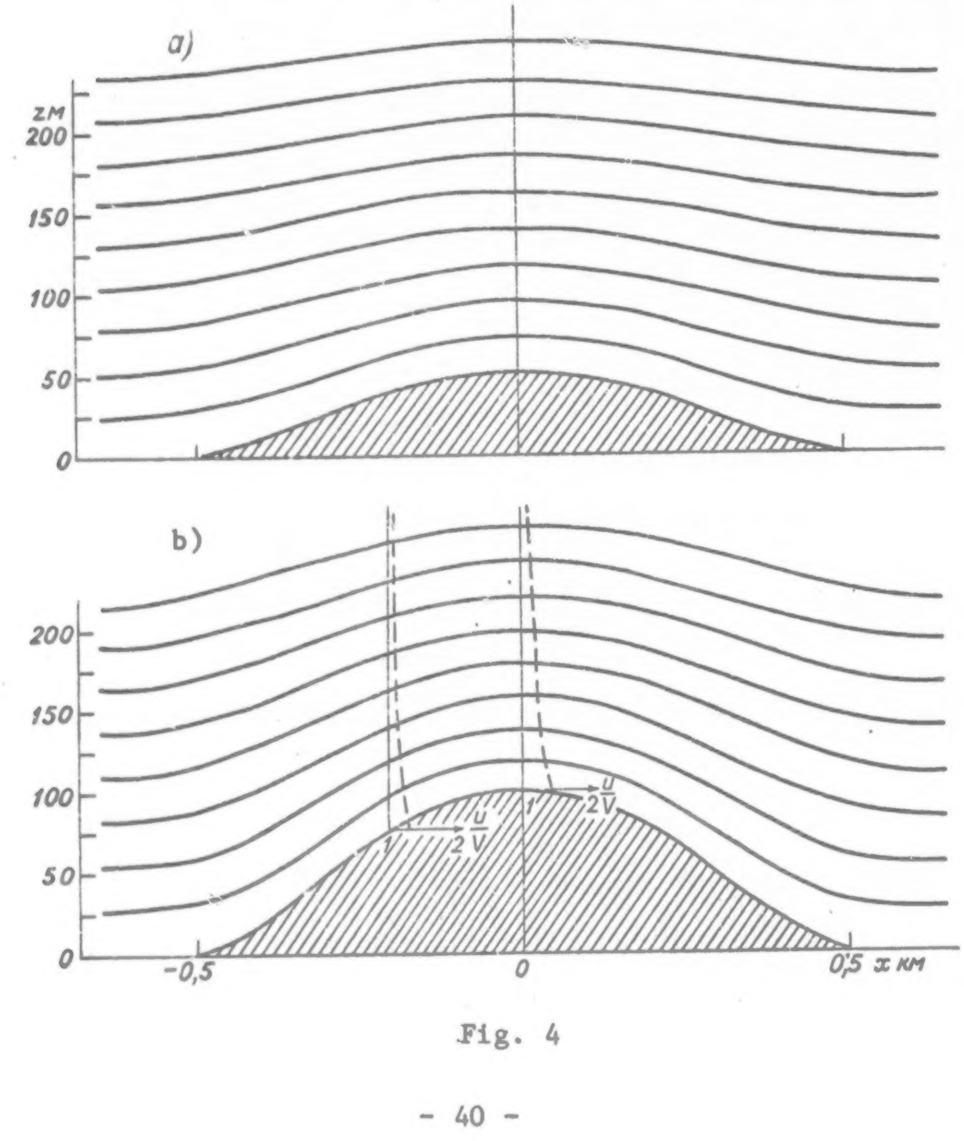

Fig. 4

The geometry of the constructed potential flow is illustrated in Fig. 4, which shows the results of a calculation of the streamlines, performed on a Ural-4 computer. Fig. 4 a pertains to the case $h_0 = 50$ m, $a = 500$ m; and Fig. 4 b, to the case $h_0 = 100$ m, $a = 500$ m.

In addition, for several points of the relief, Fig. 4 shows vertical profiles of the horizontal component and the flow velocity u referred to the velocity of the incoming flow v (dashed curves). As should have been expected, the calculations show that near the top of the hill, the flow velocity increases (the streamlines are condensed), whereas at the foot of the hill the flow velocity decreases (the streamlines are spaced out).

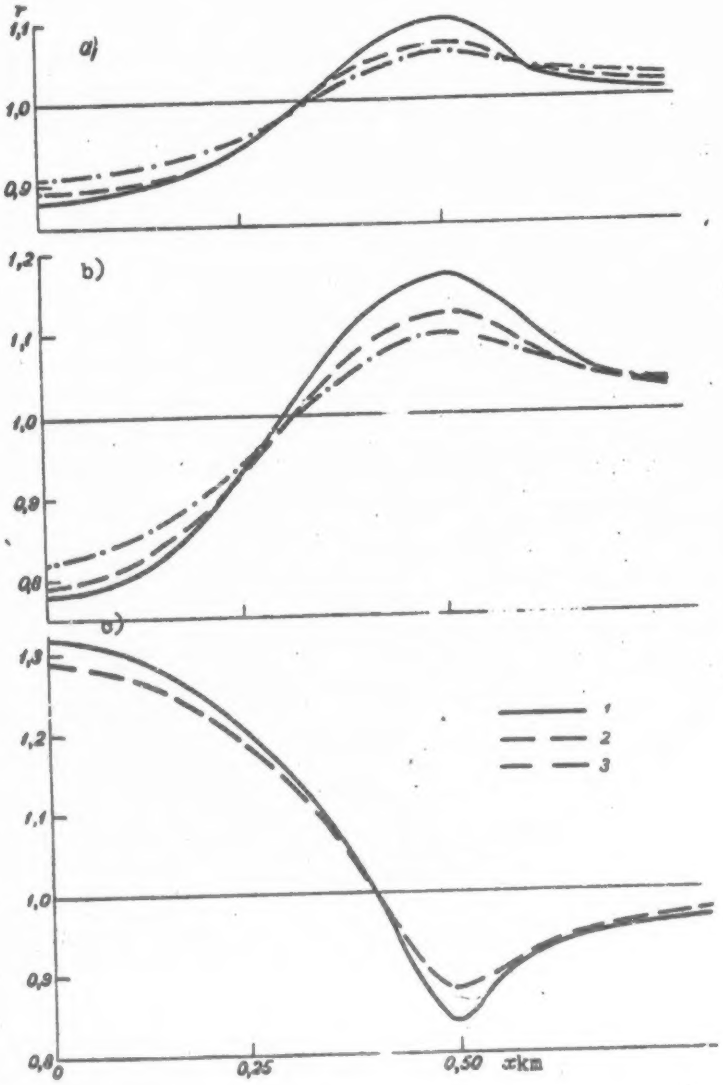

Fig. 5
$a - h_0 = 50$ m, $б - h_0 = 100$ m, $в - h_0 = -100$m, (Depression)
$1 - H_0 = 50$ m, $2 - H_0 = 100$ m, $3 - H_0 = 200$ m,

After the calculation of the streamlines, it is not difficult to determine the correction factor r entering into (24) and to apply it to the necessary source height. The corresponding results are shown (Fig. 5 a, b, and c) for sources located at various points of the leeward slope of the hill shown in Fig. 4 a, one curve pertaining to the source with height $H_0 = 50$ m and the other to $H_0 = 100$ m. It is evident that when the source is located at the top of the hill, where the streamlines are condensed, $r<1$, i. e., the source height should be less than in a level area, and when the source is located on the slope of the hill, $r>1$. If one considers that the maximum ground concentration is inversely proportional to the square of the source height, one finds that the largest variations of the maximum ground concentration may reach 25-50% for $H_0 = 50$ m and respectively 20-40% for $H_0 = 100$ m.

Comparison of Figs. 5 a and 5 b shows that as the height of the hill h_0 or the steepness of the slopes h_0/a increases, the correction for the relief increases. For example, for $H_0 = 50$ m, the maximum correction factor r is 1.16 at $h_0 = 100$ m and 1.1 at $h_0 = 50$ m.

The results are close to those obtained in the preceding section by another method.

A considerable disadvantage of the potential flow scheme discussed, particularly as compared to the scheme of the preceding section, is the symmetry of flow on the windward and leeward slopes. However, if one considers that as the wind direction changes there is also a change in the relative position of the slopes, the results obtained may be used for an overall evaluation of the influence of the relief without separating the windward or leeward sides.

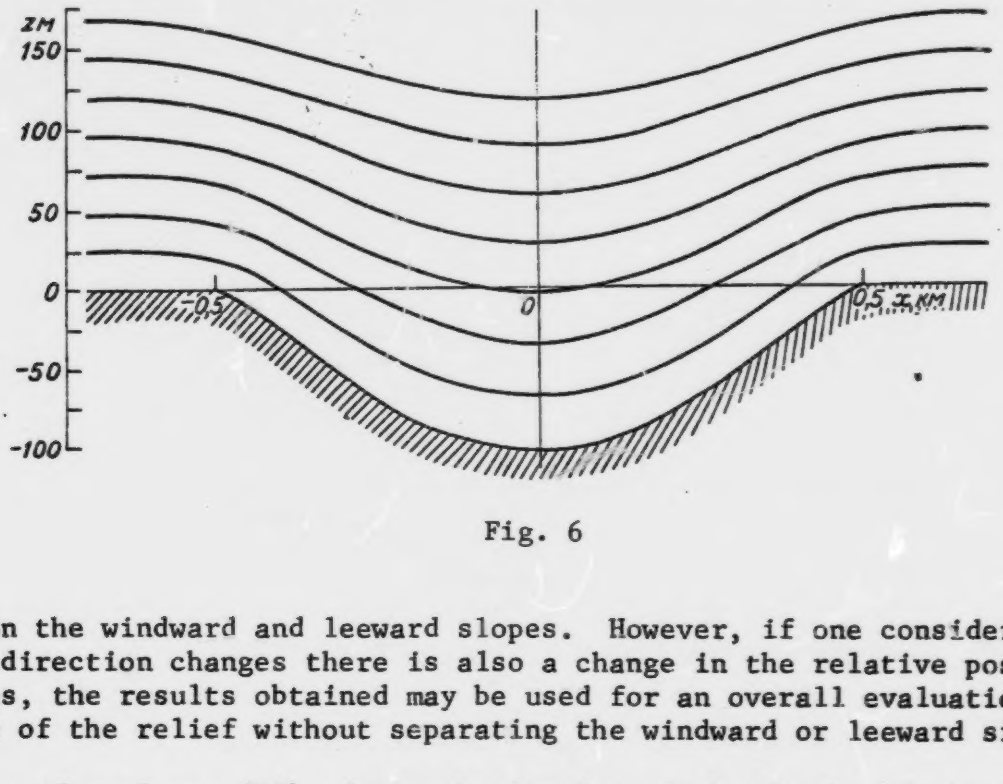

Fig. 6

The conformal map (25) after substitution of $-h_0$ for h_0 may be used to construct a potential flow above a depression whose half-width is equal to a, and whose depth is h_0. The streamlines of this potential flow for the case

h_0 = 100 m and a = 500 m are shown in Fig. 6, and the correction factor r in Fig. 5 c, in which one curve pertains to H_0 = 50 m and the other to H_0 = 100 m. As is evident from these figures, in the case of a depression the maximum value of r for H_0 = 50 m is 1.32, which corresponds to a 70% increase in the maximum concentrations of the impurity, whereas for a hill of the same height and width, the maximum value of r is 1.18.

The results obtained may be extended to regions with boundaries of more complex form. A relatively broad category of maps is obtained, for example, by means of Cauchy integrals [9]

$$t = \tau + \frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{l(s)\,ds}{s-\tau}. \tag{29}$$

The form of the function $l(s)$ is determined by the equation of the boundary of the physical region of flow, but it is simpler to take some function $l(s)$, and to obtain the equation of the boundary from (29). In particular, one can thus obtain an expression for the potential flow in the vicinity of two or more hills lined up in a row.

4. In conclusion, we shall consider the possibility of development of these approaches with the aim of providing them with a more rigorous basis and of broadening the scope of their application.

A natural extension of work on the consideration of the influence of turbulent viscosity in the vicinity of the underlying surface is the derivation of a solution of the boundary layer equation. Above a curvilinear surface, such an equation may be obtained from a system of equations of motion if flow coordinates (ϕ, ψ) are used and small terms are discarded, as was done, for example, in [13]. For a sufficiently smooth topography, the boundary layer equations thus obtained are of the form

$$Hu\frac{\partial u}{\partial\varphi} + Hw\frac{\partial u}{\partial\psi} = \frac{\partial}{\partial\psi}k\frac{\partial u}{\partial\psi} - \frac{H}{\rho}\frac{\partial p}{\partial\varphi}; \tag{30}$$

$$\frac{1}{p}\frac{\partial p}{\partial\psi} = 0; \quad \frac{\partial(Hu)}{\partial\varphi} + \frac{\partial(Hw)}{\partial\psi} = 0,$$

where u and w are the velocity components of the flow along the directions ϕ and ψ, the boundary conditions for which are given by the relations

$$\text{for } \psi = 0: \quad u = w = 0;$$
$$\text{for } \psi \to \infty: \quad u = V(\varphi).$$

Here

$$H(\varphi, \psi) = \sqrt{\left(\frac{\partial x}{\partial\varphi}\right)^2 + \left(\frac{\partial x}{\partial\psi}\right)^2} \tag{31}$$

is the Lamé coefficient of flow mapping; the velocity on the external boundary of the boundary layer is

$$V(\varphi) = H^{-1}(\varphi, \psi)|_{\psi=0} = \frac{1}{H_0(\varphi)}. \quad (32)$$

The formulated problem may be solved numerically by using the method described, for example, in [1]. However, an additional preliminary simplification of this method is possible if a substitution of variables analogous to the Dorodnitsyn transformation [10] is carried out in (30). We set

$$\xi = \int H_0 \, d\varphi; \quad (33)$$

$$\zeta = \int_0^\psi H \, d\psi.$$

From the continuity equation there follows the existence of a function G such that

$$u = \frac{1}{H} \frac{dG}{d\psi}; \quad w = -\frac{1}{H} \frac{\partial G}{\partial \varphi}.$$

If the function v is defined by the equality

$$v = \frac{wH + u \dfrac{\partial \zeta}{\partial \varphi}}{H},$$

it can be shown that

$$v = -\frac{\partial G}{\partial \xi}; \quad u = \frac{\partial G}{\partial \zeta}. \quad (34)$$

Switching to the variables of (33) in equation (30) and considering that the Bernoulli equation is satisfied in the external flow, we finally obtain:

$$u \frac{\partial u}{\partial \xi} + v \frac{\partial u}{\partial \zeta} = \frac{\partial}{\partial \zeta} k \frac{H}{H_0} \frac{\partial u}{\partial \zeta} + V \frac{dV}{d\xi}; \quad (35)$$

$$\frac{\partial u}{\partial \xi} + \frac{\partial v}{\partial \zeta} = 0.$$

The boundary conditions for this equation are

$$\begin{aligned} &\text{for } \zeta = 0: \quad u = v = 0; \\ &\text{for } \zeta = \infty: \quad u = V(\xi). \end{aligned} \quad (36)$$

For a sufficiently gentle topography, the ratio H/H_0 depends relatively little on ξ and may be assumed equal to unity. The problem of flow past a curvilinear shape is now reduced to the problem of the boundary layer on a plane wall with a given pressure gradient, which has been studied in some special cases. Thus, for example, for a constant k and an exponential dependence $V(\xi) = c\xi^m$, the solution obtained by Faulkner and Scan [10] is

$$\frac{u}{V} = \Phi'(\eta, \beta);$$

where

$$\eta=\zeta\sqrt{\frac{1}{k\beta}\frac{dV}{d\xi}};\quad \beta=\frac{2m}{m+1}. \qquad (37)$$

Tables of the function $\Phi'(\eta;\beta)$ are given, for example, in [10]. For m = 0, a solution of the Blasius problem of flow around a flat plate is obtained from (28); the case $m>0$ corresponds to different parts of the windward slope, and the case $-1<m<0$ corresponds to the leeward slope. For $m>0.0904$ in the given class of flows, there can be no separation at any values of m, and at lower values of n the solution is applicable only up to the separation point.

As an example, Fig. 7 shows graphs, calculated by means of (37), of the dependence u/V on the dimensionless argument for the values β = 1, 0, -0.14, and -0.2 (respectively, n = 1, 0, -0.065, and -0.0904). The same figure gives the experimental points obtained by S. M. Gorlin and I. M. Zrazhevskiy [7] by subjecting a model of the hill shown in Fig. 1 to a test in a wind tunnel of Moscow State University.

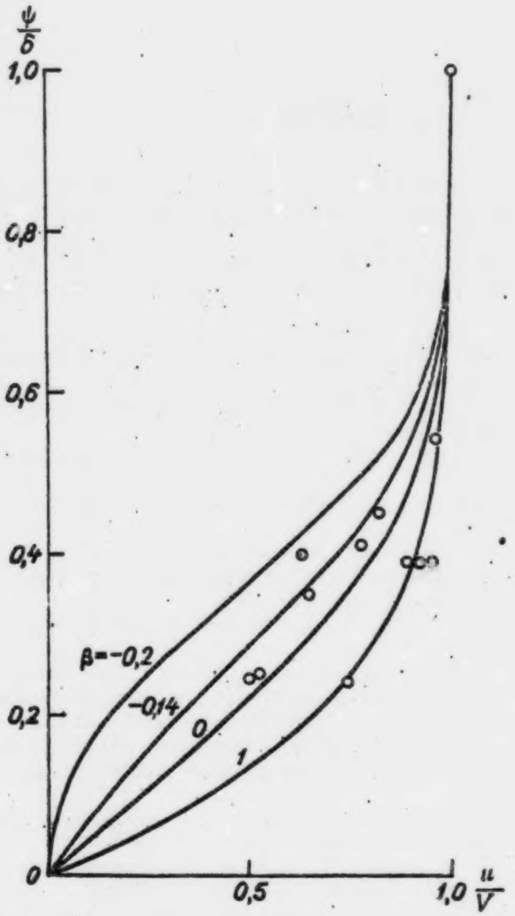

Fig. 7

The most interesting conclusion may probably be reached by combining both of the approaches presented in this paper, i. e., by splicing together the solution of the boundary layer equations with the potential flow velocities.

In so doing, to a first approximation, the reverse influence of the boundary layer on the external flow may be considered by shifting the streamlines of potential flow to a distance of the order of the displacement thickness. Since on the windward slope the potential flow velocity decreases with increasing height, while the wind velocity in the boundary layer increases with the height, it becomes understandable that the longitudinal component of the wind velocity should reach its maximum value at some distance from the underlying surface. This is supported by experimental data both for solid walls [8] and for a disturbed surface [15]. At the present time, quantitative estimates of this effect are being made.

Having thus obtained the field of the horizontal and vertical velocity of the flow, one can obtain a numerical solution of equation (3) in accordance with the scheme presented above.

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ABSORPTION OF GASEOUS IMPURITIES BY FOG DROPLETS

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From Trudy, Glavnaya Geofiz. Observat. im. A. I. Voeykova, No. 234, p. 80-84, (1968)

It has been observed that fogs are frequently associated, in the ground layer of air, with the highest content of noxious substances discharged by industrial enterprises, automobile transportation, and other sources. In London, Los Angeles, New York, and some other cities, under certain meteorological conditions, fogs change into smogs, which have an extremely adverse influence on the health of the population.

The various aspects of the influence of fogs on the diffusion of atmospheric impurities have been treated theoretically in a number of studies [1, 2, etc.].

The turbulent diffusion of a gaseous impurity from a point source in the presence of fogs is approximately described by the equation.

$$u\frac{\partial q}{\partial x}=\frac{\partial}{\partial z}\,k_z\frac{\partial q}{\partial z}+\frac{\partial}{\partial y}\,k_y\frac{\partial q}{\partial y}-\alpha q. \qquad (1)$$

Here u is the wind velocity along the x axis, k_z and k_y are respectively the vertical and horizontal components of the turbulent diffusion coefficient, the x axis is parallel to the main direction of the wind, the y axis is perpendicular to it in the horizontal plane, the z axis is vertical upward, and q is the impurity concentration at points not directly located in the zone where the impurity is washed out by separate drops. Calculations quoted in the literature [2] show that equation (1) is valid for characteristic values of the number and dimensions of the fog droplets.

The characteristics of the structure of the atmospheric boundary layer are taken into account by the variation of u and k_z, and the use of numerical methods makes it possible to carry out the investigation for arbitrary approximations of these functions.

The term aq in equation (1) takes into account the absorption of the impurity by the fog, caused by the presence of a polydisperse system of water droplets in the air, and may be expressed as follows:

$$\alpha q=\int_0^\infty N(r)\,P(r)\,dr. \qquad (2)$$

This absorption results in a redistribution of the impurity in the boundary layer of the atmosphere and in an increase of the total amount of noxious substances near the underlying surface [1]. The dissolution of gaseous substances in the droplets usually increases their toxicity.

$N_{(r)}$ is the distribution function of the fog droplets in size (radii) r. To date the A. Kh. Khrgian - I. P. Mazin distribution function [7] has found extensive applications.

P(r) is the total amount of impurity absorbed per unit time by a fog droplet of radius r. The determination of this quantity is a complex problem, since the fog droplets are in constant motion. However, even for the stable stratification characteristic of fogs, the microscale of the atmospheric turbulence substantially exceeds the size of the largest droplets. As a result, the displacement of the droplets together with the air stream does not affect the quantity P(r), which is determined only by the molecular diffusion of the impurity toward the droplet. For this reason, the magnitude of P(r) depends only on the flow around the fog droplet because of its settling by gravity. Neglecting the effect of flow around the droplet

$$P(r) = 4\pi Dqr. \tag{3}$$

Here D is the coefficient of molecular diffusion of the impurity in air. In deriving this formula, the boundary condition used is the hypothesis of complete absorption of the impurity on the surface of the droplet, which is usually fulfilled. V. G. Levich [5] points out that for gases highly soluble in water, the rate of their absorption on the surface of the droplet is determined only by the rate of diffusive supply, i. e., the processes considered follow diffusion kinetics. Formula (3) has been known for a long time and widely applied in various investigations: [1, 2, 5, 6, etc.].

In [1] and [2], a formula is given for calculating the coefficient α, based on the function proposed by Khrgian-Mazin for N(r) and formula (3) for P(r). Its use has made it possible to solve the problem of influence of fogs on the diffusion of impurities to a first approximation. The object of the present paper is to find a correction to the quantity P(r), caused by the flow of an airstream around a droplet during its settling, from the solution of the equation of molecular diffusion for a moving medium:

$$\Delta c = \mathrm{Pe}\, \mathrm{V}\, \mathrm{grad}\, c. \tag{4}$$

Here c is a dimensionless concentration of the impurity near the droplet, normalized to the quantity q; the quantity c is a function of the dimensionless radius vector of point r, normalized to the droplet radius R_0; the velocity vector of the motion of the droplet relative to the medium V is normalized to the settling rate of the droplet u_0. The Péclet number Pe is the determining parameter for the process studied.

$$\mathrm{Pe} = \frac{R_0 u_0}{D} = \mathrm{Re}\,\mathrm{Pr}; \quad \mathrm{Re} = \frac{R_0 u_0}{\nu}; \quad \mathrm{Pr} = \frac{\nu}{D}. \tag{5}$$

Here ν is the molecular viscosity of air, and Re and Pr are the Reynolds and Prandtl numbers. The quantities ν and D for air are close to one another, i. e., $\mathrm{Pr} \approx 1$, $\mathrm{Pe} \approx \mathrm{Re}$ [5, 6]. For droplet radii R_0 characteristic of a fog and settling rates u_0 determined by them, the values of Pe and Re are substantially less than unity and reach 0.2-0.3 for only the largest droplets. Under such conditions, approximate formulas of Stokes and Oseen are known for V [4]. The Stokes formula was obtained by neglecting the inertia terms in the equation of motion for a viscous liquid and applies only to very small distances from the droplet surface. The Stokes velocity distribution was used in the study of many problems [6], [8], [9], similar in mathematical formulation to the problem of interest to us (evaporation of droplets, heat emission from spherical bodies exposed to blowing, etc.). As indicated in [4], Oseen's solution for low given Re values yields better results at a considerable distance from the droplet than does the Stokes solution.

We shall utilize the smallness of the parameter Pe and seek the solution of equation (4) in the form of a series in powers of the small parameter $\varepsilon = \mathrm{Pe}$

$$c = c_0 + \varepsilon c_1 + \ldots \tag{6}$$

Substituting (6) into (4) and equating terms in ε of the same order of smallness, for the zero approximation to the desired solution we obtain the Laplace equation

$$\Delta c_0 = 0, \tag{7}$$

for the first approximation, the Poisson equation

$$\Delta c_1 = \mathbf{V} \operatorname{grad} c_0 \tag{8}$$

etc.

For the zero approximation, the same boundary conditions on the surface of the sphere and at infinity are used as for the complete solution of equation (4):

$$\begin{aligned} &\text{при } r = |\mathbf{r}| = 1 \quad c_0 = 0; \\ &\text{при } r \to \infty \quad c_0 \to 1. \end{aligned} \tag{9}$$

The solution of (7) for a spherically symmetrical region is of the form

$$c_0 = A + \frac{B}{r}. \tag{10}$$

For boundary conditions (9) for P(r), formula (3) results from (10), i. e., as should have been expected, the zero approximation describes the absorption of an impurity that is stationary relative to the medium of droplets.

For c_i at $i \geq 1$, homogeneous boundary conditions are assumed.

On the basis of the first approximation, we shall evaluate the correction to the absorption of an impurity by a droplet caused by settling of the latter. The solution of equation (8) is written in general form via the Green function [3]

$$c_1(\mathbf{r}) = -\frac{1}{4\pi} \iiint G(\mathbf{r}, \varrho) \mathbf{V}(\varrho) \operatorname{grad} c_0(\varrho) d\varrho. \tag{11}$$

Here ϱ is the radius vector of a point with variable coordinates located inside the area of solution and $d\varrho$ is the volume element

$$G = G_1 + G_0, \tag{12}$$

G_1 and G_0 are respectively the singular and nonsingular parts of the Green function.

The singular part of the Green function has the following form:

$$G_1(\mathrm{r}, \varrho) = \frac{1}{4\pi} \frac{1}{|\mathrm{r} - \rho|}, \tag{13}$$

where

$$\frac{1}{|\mathrm{r} - \rho|} = \sum_{k=0}^{\infty} R(r, \rho) P_k(\cos\theta); \tag{14}$$

$P_k(x)$ are Legendre polynomials, θ is the angle between vectors r and ϱ, and r and ρ are the moduli of these vectors.

$$R(r, \rho) = \frac{r^k}{\rho^{k+1}} H(\rho - r) + \frac{\rho^k}{r^{k+1}} H(r - \rho), \tag{15}$$

where H(x) is the Heaviside unit function,

$$H(x) = \begin{cases} 0 \text{ for } x < 0; \\ 1 \text{ for } x > 0. \end{cases}$$

In order for the nonsingular part of the Green function G_0 to satisfy the boundary conditions, it must be chosen in the following form:

$$G_0 = -\frac{1}{4\pi} \sum_{k=0}^{\infty} P_k(\cos\theta) \frac{1}{r^{k+1}\rho^{k+1}}. \tag{16}$$

From (10) it follows that

$$\operatorname{grad} c_0(r) = -\frac{B\mathrm{r}}{r^3}. \tag{17}$$

We shall subsequently use a spherical coordinate system whose origin is at the center of the droplet, and the polar axis is directed vertically downward.

Equation (14) will then be rewritten as

$$\frac{1}{(\mathrm{r} - \rho)} = \sum_{k=0}^{\infty} R(r, \rho) \Big[P_k(\cos\vartheta_r) P_k(\cos\vartheta_\rho) + \tag{18}$$
$$+ 2 \sum_{n=1}^{k} \frac{(k-n)!}{(k+n)!} \cos(\varphi_r - \varphi_\rho) P_k^n \cos(\vartheta_r) P_k^n \cos(\vartheta_\rho) \Big].$$

Here quantities ϑ and φ with subscripts r and ρ are the coordinate angles of the corresponding vectors, and $p_k^n(x)$ are the associated Legendre polynomials.

The solution for $c_1(r)$ is now written in the following form:

$$c_1(r, \theta, \varphi) = \frac{B}{4\pi} \int_0^{2\pi} d\varphi_\rho \int_0^{\pi} \sin\vartheta_\rho \, d\vartheta_\rho \int_1^{\infty} V_\rho d\rho \sum_{k=0}^{\infty} \Big[\frac{r^k}{\rho^{k+1}} H(\rho - r) +$$
$$+ \frac{\rho^k}{r^{k+1}} H(r - \rho) - \frac{1}{\rho^{k+1} r^{k+1}} \Big] P_k(\cos\vartheta_r) P_k(\cos\vartheta_\rho). \tag{19}$$

In deriving (19) it was considered that

$$\int_0^{2\pi} d\varphi_\rho \sum_{n=1}^{\infty} \frac{(k-n)!}{(k+n)!} \cos n(\varphi_r - \varphi_\rho) P_k^n(\cos\vartheta_r) P_k^n(\cos\vartheta_\rho) = 0$$

and

$$\mathbf{V}(\rho) \operatorname{grad}(\rho) = V_\rho \operatorname{grad} c_0.$$

The formula for the radial component of the dimensionless relative wind velocity V_p according to Oseen is

$$V_\rho = -\frac{3}{2}\frac{1}{\mathrm{Re}\,\rho^2}\left(1+\frac{3}{8}\mathrm{Re}\right) - \frac{\cos\vartheta_\rho}{\rho^3} - \frac{3e^{-\frac{\mathrm{Re}\,\rho}{2}(1-\cos\vartheta_\rho)}}{2\,\mathrm{Re}\,\rho^2}\left[1 + \right.$$
$$\left. + \frac{\mathrm{Re}\,\rho}{2}(1+\cos\vartheta_\rho)\right] + \frac{3}{\mathrm{Re}}\frac{\cos\vartheta_\rho}{\rho^3} e^{-\frac{\mathrm{Re}\,\rho}{2}(1-\cos\vartheta_\rho)} \tag{20}$$

When this formula is used, better results should be expected than when the Stokes formula is employed, since c_1 is expressed in terms of the velocity field over the entire space, and not only in the area adjacent to the droplet.

In order to solve the problem of absorption of an impurity by a droplet, it is necessary to define the total flow of impurity P_1

$$P_1 = 2\pi D R_0^s \int_0^{\pi} \sin\vartheta_r \left.\frac{\partial c_1}{\partial r}\right|_{r=1} d\vartheta. \tag{21}$$

It is much simpler to find P_1 than to determine the solution for c_1. Indeed, if one considers that because of the orthogonality of the Legendre polynomials the contribution to P_1 is made only by the term of the series entering into (19) corresponding to $k = 0$, then

$$P_1 = 4\pi D\alpha B \frac{\partial}{\partial r}\int_0^{\pi} \sin\vartheta_r\, d\vartheta_r \int_1^{\infty} V_\rho\, d\rho \left[\frac{1}{\rho} H(\rho - r) + \right.$$
$$\left.\left. + \frac{1}{r} H(r-\rho) - \frac{1}{r\rho}\right]\right|_{r=1}. \tag{22}$$

After some simple but cumbersome transformations we find that

$$P_1 = -\frac{1}{4} P_0 \mathrm{Pe}\,\mathrm{Re} \simeq -\frac{1}{4} P_0 \mathrm{Re}^2, \tag{23}$$

where P_0 is the flow of impurity onto the droplet in the zero approximation.

Finally,

$$P \simeq P_0 + P_1 \simeq P_0\left(1 - \frac{1}{4}\mathrm{Re}\,\mathrm{Pe}\right). \tag{24}$$

From the solution obtained it follows the motion of fog droplets slightly decreases the absorption of the impurity from air, but this correction does not exceed a few per cent. This permits the use of formula (3) in studying the characteristics of diffusion of gaseous impurities in fogs.

The results obtained in the present paper may be applied to the evaluation of the trapping of an impurity by cloud droplets, to the study of evaporation of fine droplets, etc. In particular, from the solution obtained it follows that at low Re numbers and assuming an Oseen-type flow, the evaporation of a falling droplet is somewhat less than the evaporation of a stationary droplet. As in the case of the problem considered above, this is also because of the fact that the first-approximation correction has a sign opposite to the sign of the flow in the zero approximation.

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RECORDING OF DUST CONCENTRATIONS IN THE ATMOSPHERE

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In organizing a system for control of the degree of atmospheric pollution with industrial discharges, it is very important to develop methods for recording the concentration of noxious substances in the ground layer of air.

At the present time, determinations of dust and ash concentrations in the atmosphere are made by means of the suction method [1], which yields discrete values of the weight concentration averaged over 20 minutes.

The accuracy of the method is low, and large random errors are possible. An increase in the accuracy and decrease in the interval of sampling are associated with considerable technical difficulties.

The use of instruments and techniques providing for automatic recording and processing of data makes it possible to obtain time and space characteristics of concentration fields with a great accuracy and reliability.

Among the methods for studying aerosols that offer the possibility of a simple conversion of the measured quantities into an electric signal and hence its automatic recording (ionization, radiometric, electric quantities, etc.), the optical methods, which are relative, have become comparatively popular. They permit the determination of the concentration without precipitation of the solid phase of the aerosol, and quick response measurements in an undistorted flow.

Methods which involve the use of precipitation of the solid phase on a filter make it possible to increase the sensitivity and also to perform a further analysis of the aerosol studied (chemical, gravimetric, dispersion analysis).

A convenient method is the determination of the concentration from the optical density of the solid phase of the aerosol deposited on a filter, since by obtaining the relative value of the concentration, one can switch to a constant calibration of the instrument and to the determination of the concentration by weight. The humidity content of air has no appreciable influence on the optical density of the filter, but depends on the physical properties and the particle size composition of the aerosol studied.

A filtration method using an automatic collection of samples from the atmosphere and a photometric determination of the aerosol concentration are used in many countries. In Czechoslovakia, an instrument has been constructed for automatic sampling and measurement of aerosol samples, i. e., an automatic recording aerosol concentrometer [3]. It operates on the principle of ultrafiltration by means of a tape membrane filter 15 mm wide which during the sampling moves continuously at rates from 6 cm/hr to 18 cm/hr. Simultaneously with the sampling, photometric readings are taken on the tape (the absorption of light by the aerosol track on the tape filter is measured) in order to obtain the variation of the aerosol concentration with time. Each value is averaged over 2 or 6 min. Thus, the instrument records the variation of the concentration of aerosols in the course of 8-24 hr, and the sample on the filter is kept for further processing, mainly microscopic. In determining the weight concentration for each type of aerosol, it is necessary to carry out a multiple calibration of the instrument.

The weight of the sample of solid-phase aerosol on the filter is determined by measuring the change of the optical density of the filter. The light flux I_0, which has passed through the filter alone, and the light flux I, which has passed through the same filter with the collected solid-phase aerosol I, are related by the Lambert-Beer law as follows:

$$I = I_0 e^{-kl}, \qquad (1)$$

where k is the light absorption coefficient and l is the path length in the given medium.

Known instruments of this type [3] can record only relative values of the aerosol concentration. However, according to the existing experimental data, the values of coefficient k are constant for 24 hours at the same location with a sufficient degree of accuracy. Their change with time can be related to the daily variation of meteorological elements and to the change of the conditions of discharge from the sources of particles. On this basis, a method for recording dust concentration that provides a constant calibration of the instrument by the gravimetric method (during a certain period of time) with continuous recording of the optical density of the dust sample on the filter is proposed in the present paper.

The optical density of the filter with the collected sample is given by the relations

$$D = \lg\frac{I_0}{I} \text{ или } D = \varepsilon l, \qquad (2)$$

where $\varepsilon = 0.4343k$.

The weight of the sample of solid-phase aerosol on the filter may be expressed as

$$\Delta = P - P_0 = Sl\gamma,$$

where P_0 is the weight of the filter alone, P is the weight of the same filter with the sample, which occupies an area S, and γ is the specific gravity of the sample on the filter. It then follows from (2) that

$$D = \varepsilon \frac{P - P_0}{S\gamma}. \qquad (3)$$

For the weight concentration $q = \frac{\Delta}{V_0}$ we obtain from (3)

$$D = \varepsilon \frac{V_0 q}{S\gamma} \text{ или } q = \frac{1}{0{,}4343} D \frac{S\gamma}{kV_0}, \qquad (4)$$

where V_0 is the volume of air pumped through the filter and reduced to standard conditions.

It is apparent from (4) that the weight concentration of the aerosol q may be determined via the optical density of the filter, knowing the coefficient k, which is a quantity characteristic of each aerosol and depends on its physical properties and dispersity.

The method essentially consists in the following. The tape filter is weighed before and after the sampling, processed in a photometric instrument to determine the decrease of the light flux in relative units, then the calibration coefficient $M = \frac{\Delta}{\sum_{i=1}^{n} N_i}$, where $\sum_{i=1}^{n} N_i$ — is the total change of the light flux, is determined. The calculation of the concentration at any instant of time is defined as $Q = MN_i$, where N_i is the change of the light flux on the given portion of filter.

To record the dust concentration over a longer period of time, use is made of an intake tube permitting collection of the sample on the filter, suction of air through the filter, and rewinding of the tape filter. Subsequent gravimetric and photometric analyses are carried out in the laboratory, thus simplifying the processing of the tapes. If necessary, the sampler may be combined with the photometric instrument. In this case, the density of the sample is measured and recorded during the sampling.

The sampler includes an aspirator with an air flowmeter and a cartridge with a tape transport system. The tape filter is wound inside the cartridge from the feeding reel to the take-up reel by means of a synchrous motor via a reducer. The tape passes in front of a slit with a nozzle, from which the air, after passing through the filter, is sucked into an air tube connected to the flowmeter and aspirator.

To test the method, samples were taken during an 8-hour interval on a fine-fibered LFS-250 tape filter. The transport rate of the filter was 6 cm/hr, the slit size was 10 x 30 mm, and the exposure of each portion of the filter, 10 min. The aspirator provides for an air flow of 50 l/min and is designed for operation on 220 V alternating current.

The system for photometric processing of the filter tape (Fig. 1) consists of the tape transport mechanism of a recording photometer using the simplest differential circuit. The sensing elements used were FSK-2 photoresistors, and the illuminator was an 8W incandescent bulb.

The unbalanced signal is fed into an EPP-09 recorder.

This method differs from similar ones developed in other countries in the fact that the sampling is made on NEL-4 tape filter, which has better filtering properties. The photometric instrument uses a simple measuring circuit including FSK-type sensing elements.

Tests of the combined sampler and photometric instrument were also performed. The use of round AFA-30 filters of FPP fabric is possible for taking samples during a 20-minute period. In this case, there is no need for a tape transport system, the photometric analysis is performed simultaneously with the sampling, but the recording is made in the form of traces of integrated values of attenuation of the light flux as the solid phase deposits on the filter. The circuit of the photometer is identical to the one described above. A drawback of this instrument lies in the limitation of the time of sampling on one filter and in the difficulty of eliminating the influence of sunlight on the measuring circuit of the photometer.

In the development of the instrument, considerable attention was concentrated on the selection of the filtering material, since its characteristics determine the accuracy of the method. The applicability of filters to the method is determined by their mechanical, filtering and optical properties.

Tests were made on filters of cellulose filter paper, membrane filters, and filters from fine-fiber polymer materials FPP-15, NEL and LFS developed at the L. Ya. Karpov NIFKhI. The cellulose-paper filters have a number of serious disadvantages in both filtering and optical properties, and in gravimetric analysis. Membrane filters are characterized by a high filtering efficiency and an adequate mechanical strength, which makes it possible to increase the accuracy of the measurements considerably as compared with the cellulose-paper filters. However, their hydraulic resistance is very high, and coarse particles deposited on the filter may fall away. Filters made of fine-fibered filtering materials are characterized by a high filtering efficiency at high linear suction velocities and by a moderate hydraulic resistance.

Disadvantages of the FPP-15 fabric are its low optical homogeneity, low mechanical strength, and the possibility of separation of the fibers during the suction of air. These disadvantages have been eliminated in NEL and LFS filters, which surpass the membrane filters in optical homogeneity.

The general accuracy of determination of the weight concentration is not a constant quantity in the absence of a rigid calibration of the instrument. The accuracy category of the recording system is 0.5, and the stability of the photometric circuit, 95%. The reproducibility of successive processing steps of the same tape lies within a single division. The overall sensitivity based on the weight concentration, obtained by processing ten filters, amounts to an average of 0.013 mg m^3/div. Without preliminary photometric analysis of the filter alone (before sampling), the magnitude of the optical inhomogeneity of the filter alone is within the total error of determination

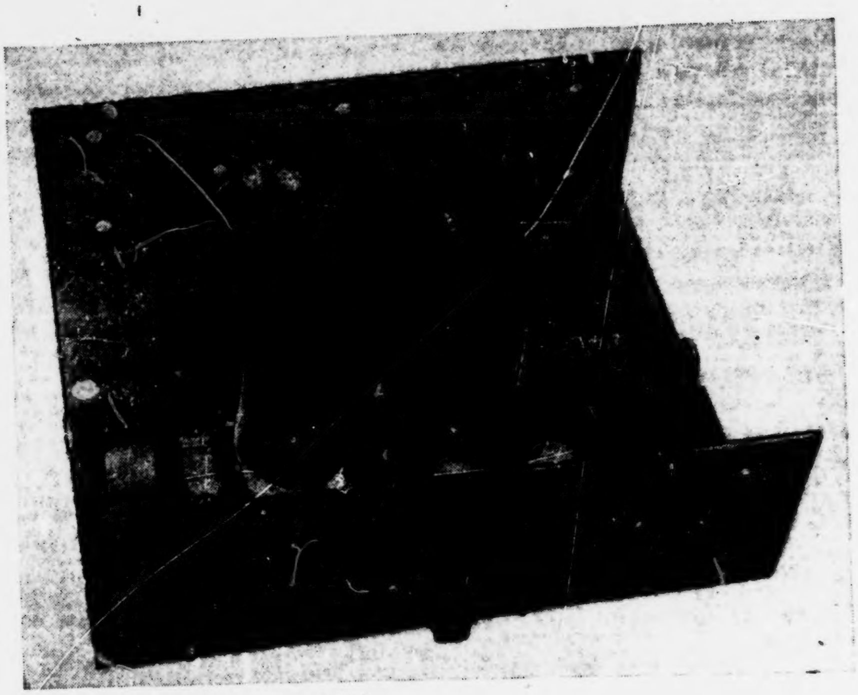


Fig. 1. Photometric instrument for processing filter tape.

of the concentration. Fig. 2 shows graphs of the change in the optical density of tape filters made of different filtering materials. The observational material is insufficient for a definitive evaluation of the filters, but one can reach the preliminary conclusion that the NEL and LFS type filters surpass the others in optical homogeneity. The technical characteristics of these filters, based on the data of [2], are given in the table. As a result of the tests, NEL filters 50 mm wide were taken for subsequent work.

Measurements made with different light filters by absorption (Fig. 3 a) and by a reflectometric method (Fig. 3 b) repeat the measurements of absorption of incident light flux without a light filter with sufficient accuracy, indicating the homogeneity of the optical properties of the particles collected on the filter.

The results obtained permit the assumption that by perfecting the measurement circuit one can increase the accuracy of the recording of the dust concentration in the atmosphere.

The models of instruments described require certain structural improvements, but on the whole they meet the requirements of the method. These instruments were used in Leningrad in the autumn of 1967 to carry out measurements of dust concentration, an analysis of which is given below.

The intake tube was located at a height of 2 m above the surface of the ground in an open area. There were no heavy sources of industrial atmospheric pollution within a radius of 2-3 km. The samples were taken in September-November in the daytime (9 A.M.-5 P.M.) with the exception of days with precipitation (20 series in all).

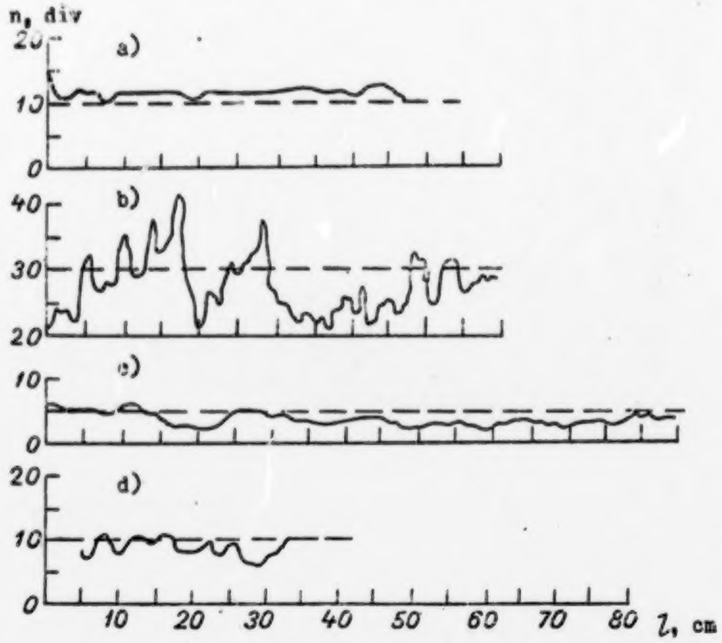
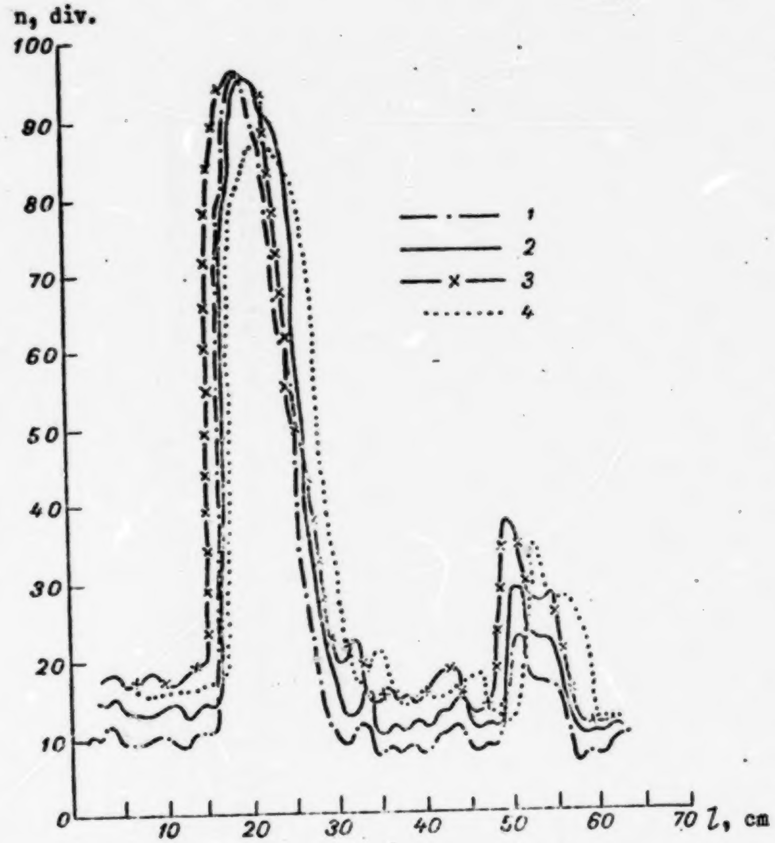


Fig. 2. Change of the optical density of tape filters from various filtering materials.
a - NEL filter; b - cellulose-paper filter;
c - LFS filter; d - membrane filter.

Table

Parameter	NEL	LFS
Resistance at air flow rate of 0.06 l/min cm^2, mm H_2O	1,8-30	1,8-30
Breakthrough coefficient, %	10	5
Tape weight, mg/cm^2	6	$0,3 \pm 0,1$
Fiber diameter, μ	1,5	$0,5 \pm 0,1$
Working temperature range, deg.	50	50

The data obtained from the recording of dust concentration in the atmosphere in the course of the day were compared with the meteorological conditions. The highest values of the concentrations, 0.4-0.9 mg/m^3, were usually observed in the morning hours. In the second half of the day, the magnitude of the dust concentration decreased. Of the total number of observations, it is possible to isolate cases where the average concentration was 0.1-0.2 mg/m^3 and underwent little change during the entire day. At the same time, the meteorological conditions were characterized by a relatively stable west-east transport at a wind velocity of 4-15 m/sec in the lower 500-meter layer.



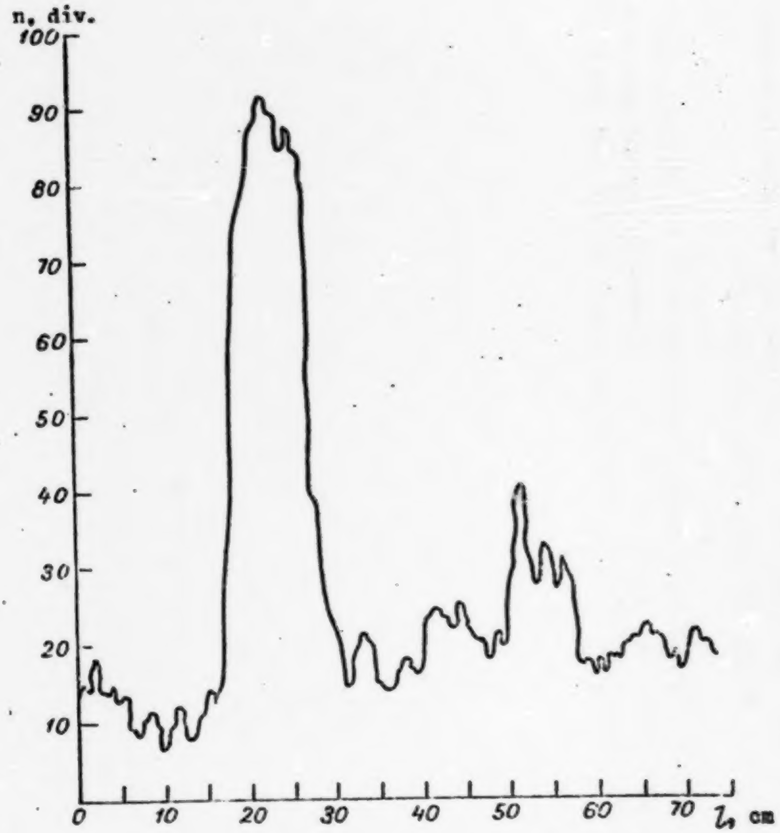


Fig. 3a. Measurements of change in the optical density of tape filter performed with different light filters, based on the absorption of light flux:

1 - with red light filter; 2 - without light filter; 3 - with green light filter; 4 - with blue light filter.

Fig. 3b. Measurement of change in the optical density of tape filter performed without light filters based on reflection of incident light flux.

As an example, Fig. 4 gives the results of processing of the recorder tapes (the sampling was made on November 20, 21, and 22 1967).

The method of measurements described above enables one to obtain the values of the weight concentration of dust with the necessary accuracy and to record the cycle of concentration change simultaneously with the sampling and afterwards.

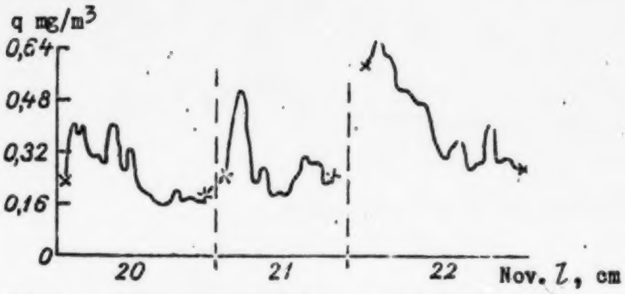


Fig. 4. Dust concentrations in atmospheric air recorded November 20, 21, and 22 1967 in Leningrad.

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COEFFICIENT OF TURBULENT EXCHANGE IN THE GROUND LAYER IN THE DAYTIME DURING THE SUMMER IN VARIOUS GEOGRAPHICAL REGIONS OF THE USSR

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In the study of the diffusion of impurities in the atmosphere and in the solution of a great many other problems it is important to know the characteristics of distribution of the vertical component of the turbulence coefficient in the ground layer of air under various climatic conditions.

It is known from theoretical studies [1, 2] and studies involving analysis of experimental material [3] that, for example, in the presence of discharges of noxious substances into the air from high smokestacks, the impurity concentration at some distance from the source increases with an intensification of turbulent exchange. A heavier air pollution at high values of the turbulence coefficient is also observed in cities, where sources of discharges of different heights are present [4]. For this reason, the study of the maximum intensity of turbulent exchange in different geographical regions is of substantial interest. According to the available literature data, the maximum turbulent exchange is usually observed in the superadiabatic state of the atmosphere, which usually occurs in summer at noontime.

Some patterns of distribution of one of the characteristics of turbulence in the ground layer were studied in [5] over the territory of the USSR under these conditions. The object of the present paper was to make an additional study of the characteristics of this distribution by using data on the vertical component of the turbulence coefficient, a component calculated by the heat balance method. This method is characterized by a certain degree of objectivity, and is independent of many hypotheses underlying other methods of calculation of the turbulence coefficient. By analyzing a large volume of experimental material [6, 7, etc.] it has now been established that in the lowest layer, which is of the order of several meters, the change of air temperature and humidity with the height is adequately described by a logarithmic law.

Representing the variations of air temperature and humidity with the height in accordance with the logarithmic law and assuming the turbulence coefficients for heat and moisture in the ground layer to be approximately equal in magnitude, we write the following formula for the vertical component of the turbulent exchange coefficient at a height of 1 m:

$$k_1 = \alpha(R - Q). \tag{1}$$

Here R is the radiation balance at the level of the underlying surface in

cal/cm^2 min; Q is the heat flow between the underlying surface and the subjacent layers of the soil in cal/cm^2 min; $\alpha = \frac{0.74}{\Delta t + 1.56 \Delta e}$, where $\Delta t°$ and $\Delta t°$ mb are the differences of temperatures and absolute humidity of air between the heights of 0.5 and 2.0 m. The numerical factors 0.74 and 1.56 were obtained by substituting the values L=600 cal/g, $p=1.293 \times 10^{-3}$ g/cm^3, $c_p=0.24$ cal/g deg and p=1000 mb.

To calculate the turbulence coefficient from formula (1), as in [5], use was made of observational material of heat balance stations for the 1 P.M. period in July during the period of operation of the stations from 1955 to 1967. Up to 1961-1962, the tables of gradient observations contained all the necessary initial data for the calculation of k_1 for each day: the measured values of R, Δt and Δe, calculated from the measured temperature and humidity of air at two levels, and Q, determined from the temperature and humidity of the soil according to the method presented in [8]. The calculation of the values of the turbulence coefficient for each day is therefore relatively easy, particularly since the value of α in (1) has been tabulated. From the values of k_1 calculated for each day, one can readily compute the mean monthly values of the turbulence coefficient for individual years and then the average for a number of years.

From 1962 on, the calculation of daily values of the heat flow in the soil was not made at the stations; its calculation for each day at a large number of stations in the course of several years is very laborious. It is of interest, therefore, to examine the possibility of using mean monthly values of the initial data for calculating the turbulence coefficient. On the basis of observational material of 30 stations (≈100 cases) located in different geographical regions, the turbulence coefficient was calculated for a number of years for 1 P.M. in July from both the mean monthly values of the initial data in individual years k'_1 ($\bar{R}$, $\bar{Q}$, $\overline{\Delta t}$, $\overline{\Delta e}$) and daily values $\bar{k}_1$(R, Q, Δt, Δe). Before 1962, the mean monthly values of the meteorological parameters on the network of heat balance stations were not computed. They were calculated by first using the mean monthly values available from a number of stations, calculated under the direction of T. A. Ogneva and kindly supplied to the author. From 1962 on, the heat flow between the underlying surface and the subjacent layers was calculated daily at all of the above-indicated stations. Results of the comparison of mean monthly values of k_1 for the individual years are shown in the form of points in Fig. 1. Mean monthly values of $\bar{k}'_1$ calculated by the heat balance method from initial data averaged over a month are laid off along the x axis, and values of $\bar{k}_1$ calculated from daily data and then averaged over the month are laid off along the y axis. Of the 100 cases considered, in only 10 was the relative averaging error

$$\Delta N = \frac{\bar{k}'_1(\bar{R}, \bar{Q}, \overline{\Delta t}, \overline{\Delta e}) - \bar{k}_1(R, Q, \Delta t, \Delta e)}{\bar{k}_1(R, Q, \Delta t, \Delta e)} \qquad (2)$$

greater than 30%; its average in absolute value was 15.3%.

Fig. 1 also compares the mean monthly values of $\bar{k}'_1$ and $\bar{k}_1$ averaged over several years at each of the 30 stations (circled points). The mean averaging error was 7.7%.

It is evident from Fig. 1 that deviations from the bisector are observed on both of its sides, with a certain exaggeration of the k_1' values calculated from initial data averaged over the month.

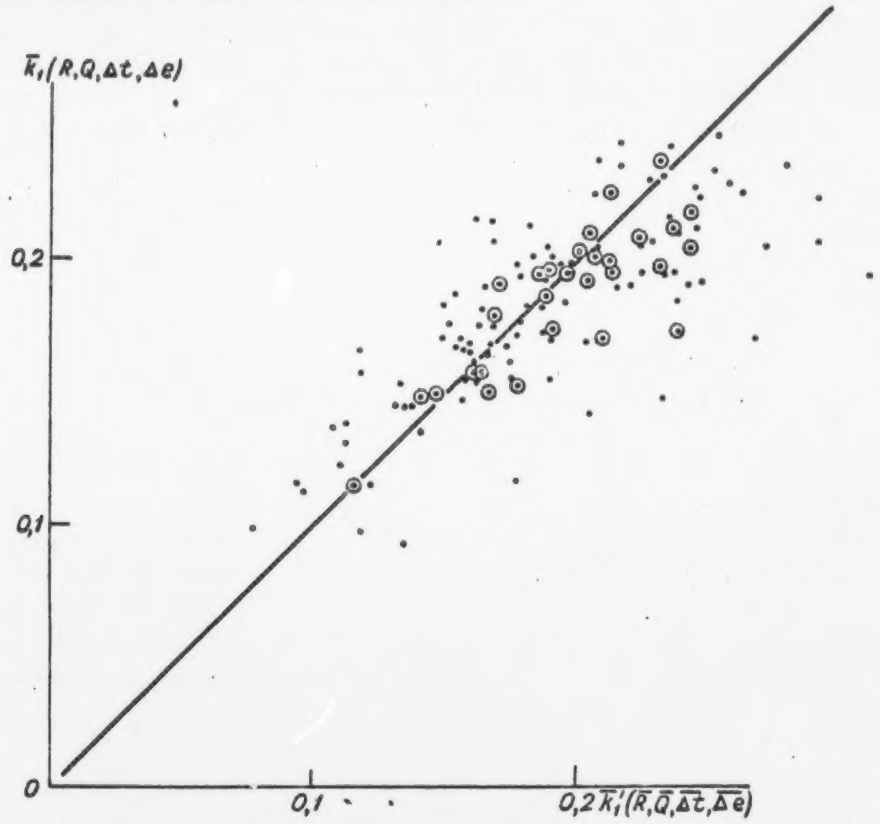

Fig. 1.

The calculation of the turbulence coefficient by the heat balance method from both daily and mean monthly initial data may in some cases involve considerable errors, for example, at low values of the difference between the radiation balance and the heat flow into the soil or at low values of the differences in air temperatures and humidity at the two levels. Allowing for the accuracy of the measurement of meteorological parameters with network instruments (0.01 cal/cm^2 min. for R and Q and 0.2° C. and 0.2 mb for Δt and Δe), possible relative errors in the calculation of the turbulence coefficient from formula (1) were determined for different values of the initial data (Fig. 2).

In determining the turbulence coefficient from formula (1), only cases assumed to contain a relative error of no more than 40% were considered. In addition, the computation of mean monthly values of k_1 from the calculated daily values was made only when the number of k_1 values computed with a relative error of 40% or less was greater than or equal to 10 per month. In addition to the above-mentioned 30 stations, the data of heat balance observations of 39 stations (total of 69 stations) were also considered for the same period. The calculation of the turbulence coefficient based on data of these stations was made only on the basis of mean monthly initial data.

The great majority of the stations are located on the European territory of the USSR, with the exception of its northeastern part, and also in Kazakhstan and Central Asia, while approximately one-third of all the stations are located on the territory of Siberia and the Far East. The series of k_1 values calculated for the individual years during the above indicated observation period from 1955 to 1967 at the different stations were found to be different as a result of both the limitations adopted in the treatment ($\frac{\Delta k_1}{k_1} \leqslant 40\%$), and an uncoordinated opening of the heat balance stations, some of which were opened in the last 2-3 years.

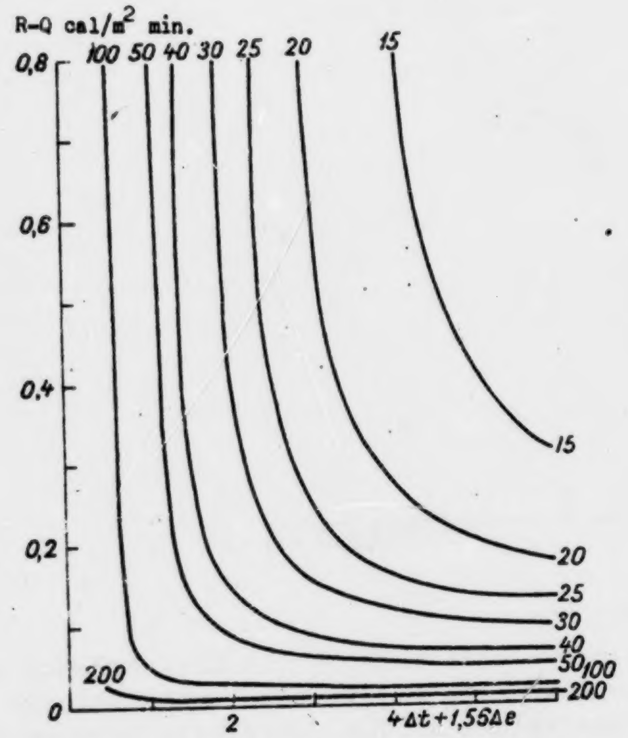

Fig. 2. Possible relative errors (%) of the calculation of the turbulence coefficient (k) by the heat balance method.

The present paper uses only the data of the existing stations, which are considered more or less representative of the heat balance observations. At 37 stations, the k_1 values calculated for the individual years were averaged over 3 years or more; at 28 stations, over 1 to 2 years, and at 4 stations, because of the above-indicated limitations of treatment, the turbulence coefficient could not be determined.

The manner in which the mean value of the turbulence coefficient deviates from the period of averaging can be determined by using, according to [9], a successive averaging over all the longer periods beginning with the last year of observations. To this end, data on the turbulence coefficient were selected at several stations with longer series of observations. Average values for 1, 2, 3, etc. years were calculated starting in 1967. Results of the calculation are shown in Table 1. Average values of k_1 from the longest observation period at our disposal (they were different at different stations) were arbitrarily taken as the norm. Deviations (%) of the mean values for 1, 2, 3, etc. years from the norm (part II of the table) were then calculated.

It is obvious from the table that for a relatively short averaging period (1-2 years), the deviation from the norm does not exceed 20% at most stations, and that deviations in excess of 30% are observed at only 2 stations.

Table 2 gives mean values of the turbulence coefficient for increasing periods of averaging and deviation from the norm (according to the data of [5]). Analysis of this table shows that at the majority of the stations considered, deviations of the norm for averaging periods of 1 to 3 years also do not exceed 20%, and at only three stations out of 26 are the deviations less than 30%. It should be noted that the averages for short periods (1-3 years) frequently differ from averages for longer periods by no more than 10%. Hence, short series of observations can be used without a large error, especially when the aim is to determine the basic patterns of distribution of some element.

Values of k_1 computed for several years or even for 1 to 2 years give some idea of the distribution of the turbulence coefficient in the ground layer over the territory of the USSR.

The average July values of the turbulence coefficient for 1 P.M. and values of k_1/u_1, where u_1 is the wind velocity at a height of 1 m, are shown in Table 3. Values of k'_1 were calculated from mean monthly initial data for individual years and then averaged over the indicated period. The k_1 values were calculated from daily initial data, then averaged over the month and over the entire period.

It is apparent from the table that the highest values of the turbulence coefficient in the ground layer (0.20-0.25 m^2/sec.) in July at noon are observed, as in [5], in the desert of Central Asia, Kazakhstan, regions of the lower Volga, and in the south of the Ukraine. In the central regions of the European territory and also in the foothills of the Southern Ural, Pamir, Tyan'-Shan', Altay, and Sayan, the values of the turbulence coefficient obtained by the heat balance method were somewhat higher (0.15-0.20 m^2/sec.) as compared to k_1 (0.12-0.15 m^2/sec.) for the same regions in [5]. As far as Transbaykal'ye, northern Siberia, and the northeast of the European territory are concerned, the k_1 values here were approximately the same in magnitude as in [5] and equal to 0.12-0.18 m^2/sec. The highest values of the turbulence coefficient are found in the regions where the highest wind velocities are observed in July, whereas on the contrary, the values of the ratio k_1/u_1 in these regions are minimum, of the order of 0.05-0.06. The maximum k_1/u_1 values (0.10 and slightly higher) are observed in the foothills, and are of the order of 0.06-0.08 on the remaining territory. The k_1/u_1 values in different regions of the USSR together with other parameters are necessary for refining the coefficient characterizing the influence of meteorological conditions on the dispersal of noxious impurities in the atmosphere [10].

Table 1

Mean Value of the Turbulence Coefficient (k_1) for Various Averaging Periods.

Year	Nikolayevskoye	Dushanbe	Gigant	Kuybyshev	Petrozavodsk	Kostroma	Telavi	Nolinsk	Solyanka	Yakutsk	Riga	Pinsk	Beregovo	Askaniya-Nova	Tamdy	Rudnyy	Khomutovo	Skovorodino
1967	0,113	0,164	0,251	0,210	0,234		0,210	0,185	0,130	0,162	0,175	0,241		0,161	0,216	0,235	0,115	0,165
1966	0,122	0,160		0,232	0,164		0,191		0,148			0,201		0,180	0,207	0,200	0,136	
1965	0,131	0,179	0,262	0,226	0,154	0,164	0,205	0,209	0,161	0,160		0,216				0,199	0,166	0,182
1964	0,128	0,175		0,236	0,166		0,197		0,164	0,175		0,202	0,276	0,205	0,235		0,188	0,178
1963	0,139	0,174	0,237		0,155	0,177	0,191		0,172			0,235	0,235		0,207	0,201	0,189	0,184
1962	0,138	0,172	0,234		0,166		0,197	0,205		0,164			0,227			0,213		0,172
1961	0,130	0,167	0,217	0,230		0,150		0,216			0,157		0,242					
1960	0,140		0,207	0,224		0,151			0,180	0,158	0,165							
1959		0,167						0,208			0,182		0,229	0,226	0,209			
1958			0,203			0,157												
1957								0,203		0,166								
1956						0,158					0,169			0,230				
1955				0,235														

Deviation (%) of the mean value of the turbulence coefficient from the norm

Averaging Period	Nikolayevskoye	Dushanbe	Gigant	Kuybyshev	Petrozavodsk	Kostroma	Telavi	Nolinsk	Solyanka	Yakutsk	Riga	Pinsk	Beregovo	Askaniya-Nova	Tamdy	Rudnyy	Khomutovo	Skovorodino
1	—19,3	—1,8	23,6	—10,6	41,0	5,1	6,6	—8,9	—27,8	—2,4	3,6	2,6	20,6	—30,0	17,7	10,3	—39,2	—4,1
2	—12,8	—4,2	29,1	1,3	—1,2	12,0	—3,0	3,0	—17,8	—3,6	—7,1	—14,5	2,6	—21,8	—1,0	—6,1	—28,0	5,8
3	—6,4	7,2	16,8	—3,8	—7,2	—5,1	4,1	1,0	—10,6	5,4	—2,4	—8,1	—0,9	—10,9	12,4	—6,6	—12,2	3,5
4	—8,6	4,8	15,2	0,4	0,0	—4,4	0,0	6,4	—8,9	—1,2	7,7	—14,0	5,7	—1,7	—1,0	—5,6	—0,5	7,0
5	—0,7	4,2	6,9	—2,1	—6,6	—0,6	—3,0	2,5	—4,4	—4,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
6	—1,4	3,0	2,0	—4,7	0,0	0,0	0,0	0,0	0,0	0,0								
7	—7,2	0,0	0,0	0,0														
8	0,0	0,0																

Table 2

Mean Value of the Turbulence Coefficient (k_1) for Various Averaging Periods.

Year	Sobakino	Riga	Nikolayevskoye	Torzhok	Pavelets	Smolensk	Askaniya-Nova	Kuybyshev	Artem Island	Solvanka	Tiyrikoyya	Kostroma	Gigant
1966	0,145	0,143	0,166	0,136	0,138		0,170	0,149	0,196	0,165	0,142		0,140
1965	0,159	0,132		0,158	0,160	0,160	0,175		0,190	0,163	0,151	0,108	0,146
1964	0,159	0,126	0,184	0,152	0,158	0,170	0,174		0,205	0,151	0,139	0,128	0,146
1963	0,156	0,127	0,186	0,143	0,161	0,157	0,173	0,156	0,197	0,166	0,134	0,133	0,141
1962	0,143	0,126	0,180	0,148	0,160	0,159	0,172	0,156	0,194	0,160	0,130	0,136	0,154
1961	0,138	0,123	0,171	0,148	0,157	0,161	0,171	0,146	0,199	0,157	0,130	0,127	0,158
1960	0,132	0,124	0,173	0,151	0,156	0,154		0,144	0,207	0,157	0,130	0,121	0,158
1959	0,131	0,124	0,173	0,148	0,151	0,149	0,179	0,146	0,207	0,158			0,148
1958	0,130	0,128	0,168	0,148	0,150	0,149	0,181	0,146	0,206	0,165		0,128	0,142
1957	0,130	0,128	0,165	0,147	0,150	0,147	0,187	0,146	0,205	0,164	0,134	0,130	
1956	0,130	0,132	0,164	0,148	0,154	0,146	0,190	0,146			0,139	0,134	
1955	0,130	0,135	0,162					0,150					
1954													

deviation (%) of the mean value of the turbulence coefficient from the norm

Averaging Period													
1	11,5	5,9	2,5	—8,1	—10,4	9,6	—10,5	—0,7	—4,4	0,6	2,2	—19,4	—1,4
2	22,3	—2,2	13,6	6,8	3,9	16,4	—7,9	4,0	—7,3	—0,6	8,6	—4,5	2,8
3	22,3	—6,7	14,8	2,7	2,6	7,5	—8,4	4,0	0,0	—7,9	0,0	—0,7	2,8
4	20,0	—5,9	11,1	—3,4	4,6	8,9	—9,0	—2,7	—3,9	1,2	—3,6	1,5	1,4
5	10,0	—6,7	5,6	0,0	3,9	10,3	—9,5	—4,0	—5,4	—2,4	—6,5	—5,2	8,4
6	6,2	—8,9	6,8	0,0	2,0	5,5	—10,0	—2,7	—0,5	—4,3	—6,5	—9,7	11,2
7	1,5	—8,2	6,8	2,0	1,3	2,1	—5,8	—2,7	1,0	—4,3	—6,5	—4,5	11,2
8	0,8	—8,2	3,7	0,0	—2,0	2,1	—4,7	—2,7	1,0	—3,7	—3,6	—3,0	4,2
9	0,0	—5,2	1,8	0,0	—2,6	0,7	—1,6	—2,7	0,5	0,6	0,0	0,0	0,0
10	0,0	—5,2	1,2	0,7	—2,6	0,0	0,0	0,0	0,0	0,0			
11	0,0	—2,2	0,0	0,0	0,0								
12	0,0	0,0											

Table 2 (Cont'd)

Year	Beki-Bent	Tamdy	Borispol'	Poltava	Kamennaya Step'	Beregovo	Nolinsk	Dushanbe	Frunze	Yakutsk	Fort Shevchenko	Vys. Dubrova	Kalmykovo
1966	0,198	0,221	0,180	0,162	0,134	0,147		0,128	0,146		0,167		0,195
1965	0,185	0,216	0,182	0,187	0,134	0,116	0,169	0,136	0,163	0,139		0,136	
1964	0,167	0,202	0,166	0,175	0,128	0,129		0,129	0,154	0,157	0,168		
1963	0,167	0,222	0,163	0,167	0,130	0,131	0,150	0,127			0,165		0,198
1962	0,172	0,222	0,165	0,169		0,133	0,150	0,124		0,155	0,178		0,203
1961	0,171	0,220	0,171	0,164	0,142		0,147	0,126		0,152	0,174		0,204
1960	0,184	0,229					0,141	0,127		0,153	0,179		0,202
1959	0,187	0,236	0,171	0,166	0,147	0,132	0,138	0,125	0,154	0,150	0,177	0,116	0,201
1958	0,190	0,242	0,168	0.167	0,148	0,129	0,148		0,151	0,148		0,118	0,201
1957					0,162	0,129	0,149			0,148		0,115	
1956									0,156			0,113	
1955									0,157			0,112	
1954									0,157			0,107	
deviation (%) of mean value of turbulence coefficient from the norm													
Averaging Period													
1	4,2	—8,7	7,1	—3,0	—17,3	14,0	13,4	2,4	—7,0	—6,1	—5,6	27,1	—3,0
2	—2,6	—10,8	8,3	12,0	—17,3	—10,1	0,7	8,8	3,8	6,1	—5,1	8,4	—1,5
3	—12,1	—16,5	—1,2	4,8	—21,0	0,0	0,7	3,2	—1,9	4,7	—6,8	10,3	1,0
4	—12,1	—8,3	—3,0	0,0	—19,8	1,6	—1,3	1,6	—1,9	2,7	0,6	7,5	1,5
5	—9,5	—8,3	—1,8	1,2	—12,3	3,1	—5,4	—0,8	—1,9	3,4	—1,7	5,6	0,5
6	—10,0	—9,1	1,8	—1,8	—9,2	2,3	—7,4	0,8	—0,6	1,4	1,1	4,7	0,0
7	—3,2	—5,4	1,8	0,6	—8,6	0,0	—0,7	1,6	0,0	0,0	0,0	0,0	0,0
8	—1,6	—2,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0			
9	0,0	0,0											
10													
11													
12													

Table 3

Mean Values of the Turbulence Coefficient (k_1) at a Height of 1 m Calculated by the Heat Balance Method and k_1/u_1 Values for 1 P.M. in July.

Station	k_1' M²/sec.	k_1 M²/sec.	k_1'/u_1 M²/sec.	Averaging Period
Khibiny	0,146	0,149	0,062	1963, 1966—1967
Petrozavodsk	0,166	0,151	0,065	1962—1967
Arkhangel'sk	0,196	0,196	0,094	1964, 1966
Kargopol'	0,140		0,070	1964
Ust'Vym'	0,161	0,158	0,074	1966—1967
Voyeykovo	0,210		0,072	1967
Nikolayevskoye	0,140	0,148	0,056	1960—1967
Tiyrikoyya	0,187	0,187	0,074	1966—1967
Riga	0,169	0,192	0,074	1956, 1959, 1961, 1967
Pinsk	0,235		0,103	1963—1967
Smolensk	0,212	0,227	0,082	1965—1967
Toropets	0,180		0,072	1961, 1965—1967
Torzhok	0,186	0,196	0,071	1958, 1965—1967
Kostroma	0,158	0,168	0,074	1956, 1958, 1960—1961, 1963, 1965
Nolinsk	0,203	0,193	0,083	1957, 1959, 1961—1962, 1965, 1967
Cheben'ki	0,160		0,050	1967
Sovetsk	0,200		0,058	1965—1967
S. I. Nebol'sin station	0,180		0,078	1966—1967
Pavelets	0,200	0,204	0,080	1963, 1965—1967
Kamennaya Step'	0,149		0,035	1957
Borispol'	0,194		0,060	1958, 1965—1966
Poltava	0,208		0,075	1958, 1964, 1966—1967
Beregovo	0,229		0,111	1959, 1961—1964
Askaniya-Nova	0,230	0,239	0,080	1956, 1959, 1964, 1966—1967
Nikitskiy sad	0,305		0,179	1966—1967
Gigant	0,203	0,212	0,088	1958, 1960—1963, 1965—1967
Astrakhan'	0,224		0,101	1958, 1963—1964, 1967
Kalmykovo	0,223	0,210	0,064	1962—1963, 1966
Ural'sk	0,206		0,061	1967
Yershov	0,206	0,203	0,060	1966—1967
Kuybyshev	0,235	0,214	0,108	1955, 1960—1961, 1964—1967
Kushnarenkovo	0,242	0,220	0,104	1966—1967
Rudnyy	0,213	0,197	0,064	1962—1963, 1965—1967
Tselinograd	0,199		0,054	1965—1966
Ogurtsovo	0,162	0,158	0,057	1965, 1966
Karasust	0,249		0,068	1966—1967
Balkhash	0,274		0,065	1965—1967
Aydarly	0,216		0,076	1964, 1967
Churuk	0,180		0,055	1965—1967
Fort Shevchenko	0,241		0,049	1966
Tamdy	0,209	0,172	0,058	1959, 1963, 1965—1967
Beki-Bent	0,190	0,186	0,070	1966—1967
Ak-Molla	0,241	0,206	0,070	1965—1966
Chardzhou	0,201		0,087	1966
Termez	0,211	0,200	0,087	1966—1967
Fergana	0,231	0,198	0,196	1964—1967
Dushanbe	0,167	0,180	0,142	1959, 1961—1967
Frunze	0,196		0,125	1964—1967
Telavi	0,194		0,104	1962—1966
Nakhichevan'	0,238	0,174	0,099	1966
Artem Island	0,265		0,053	1967
Solyanka	0,180		0,079	1960, 1963—1967
Khakasskaya	0,178		0,109	1965—1967
Kyzyl	0,188	0,198	0,109	1965—1967
Khomutovo	0,189		0,096	1963—1967
Chita	0,178		0,083	1964—1967
Mangut	0,152		0,071	1966—1967
Skovorodino	0,172		0,090	1962—1965, 1967
Tolstovka	0,177	0,153	0,071	1967
Primorskaya	0,246		0,086	1965—1967
Yakutsk	0,166		0,080	1957, 1960, 1962, 1964—1965, 1967
Turukhansk	0,122		0,068	1967
Tura	0,095		0,048	1965
Oymyakon	0,135		0,079	1967
Verkhoyansk	0,115	0,115	0,053	1964—1966

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PHYSICAL PRINCIPLES OF CALCULATION OF DISPERSAL OF INDUSTRIAL DISCHARGES IN THE ATMOSPHERE

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1. Introduction

One of the chief applications of studies of atmospheric diffusion is the calculation of dispersal of industrial discharges in the atmosphere. Studies along these lines have laid the basis for the consideration of meteorological conditions in the design and operation of enterprises discharging noxious substances into the atmosphere, and for determining the permissible discharge and the height of smokestacks at which the required air purity is ensured in the surrounding area.

To date, many studies have been published dealing with atmospheric diffusion and related investigations of turbulent exchange. In the Soviet Union, the most extensive studies have been conducted at the A. I. Voeykov Main Geophysical Observatory (GGO), the Atmospheric Physics Institute, the Applied Geophysics Institute, the Leningrad Hydrometeorological Institute, and others. Numerous studies have been made in England, the U.S.A., Japan, and other countries. A number of books and special papers [5, 6, 34, 51 etc.] have been devoted to a review of the results obtained.

The results of the completed studies have found practical applications comparatively recently. The first attempts to adjust the discharges into the atmosphere to certain meteorological characteristics were undertaken 20-30 years ago. In 1936, Bosanquet and Pearson [46] and in 1947 Sutton [52], who used his 1932 studies, proposed working formulas for determining the surface concentration of an impurity from high sources. As a result of the rapid development of industry and the associated increase in air pollution, the results of these calculations, particularly Sutton's formulas, were rapidly adopted in many countries. Interest in them grew with the start of construction of atomic reactors and the consequent need to evaluate possible air pollution by radioactive substances. From then on, studies dealing with the experimental verification of the working formulas and their further theoretical generalization expanded considerably.

In the Soviet Union, among the first studies dealing with the calculation of dispersal of industrial discharges were those carried out by G. V. Sheleykhovskiy [44], N. V. Dergachev [27] and P. I. Andreyev [1], who used Sutton's formula or similar relations.

The experimental studies performed showed that the indicated working formulas reflect, mainly in a qualitative manner, some characteristics of the propagation of impurities in the atmosphere. However, in a quantitative sense, there are considerable discrepancies between the observed and the calculated data. This has led to the introduction of correction coefficients into the working formulas and to the development of other empirical and theoretical relations. The studies of Pasquill [51], Mead [49], Hawkins and Nonhebel [50], Wipperman [53], Cramer [48], etc. have received considerable attention. They are essentially based on relations of the type of Sutton or Bosanquet-Pearson formulas. Part of these studies give a more detailed representation of the dependence of the parameters contained in the formulas on the meteorological conditions. In the practical calculation of impurity concentrations from industrial sources, it becomes necessary to consider the initial ascent as well. A considerable number of methods also have been proposed for calculating this ascent.

As a result, a large number of highly diversified working formulas are now available. However, very few methods of calculation are known which have been sufficiently approved and recommended for broad applications as standard documents in various countries. Among such documents can be included the Handbook of the German Engineering Society, Mead's method recommended to the World Meteorological Organization for calculating the dispersal of discharges from atomic reactors, etc. In the USSR, the first standard document of this kind was the work [19], officially ratified in 1963 and now generally used in the design of electric power plants. A distinctive feature of this method is its theoretical soundness and extensive experimental validation. To date, considerable experience has been accumulated on the application of the method in the USSR; it has attracted the attention of experts and found acceptance in countries of S.E.V. Council of Economic Mutual Assistance, Yugoslovia, France, Japan and elsewhere.

The problem has naturally arisen of generalizing the given method and extending it to a broader category of industrial enterprises. Heat and power stations are in the category of large sources characterized by heavy discharges of sulfur dioxide and ash, and also by a substantial overheating of the stack gases relative to the surroundings. The discharges are ejected from relatively high stacks located close to each other, and, in practice, an electric power plant may be treated as a single source. To generalize the method, it was necessary to study the conditions of dispersal of impurities in the atmosphere over a wider range of variation of stack heights and volumes and temperatures of discharges, in the presence of differences in the parameters of the individual sources, their scatter, etc.

Given below are some results of studies along these lines, forming the basis of the "Recommendations on the Calculation of the Dispersal in the Atmosphere of Noxious Substances (Dust and Sulfur Dioxide) Contained in Discharges of Industrial Enterprises" [43], ratified in 1967 by the USSR Office of State Construction, section of construction standards and regulations (SN 369-67).

2. Initial Assumptions

In the last few years, the Main Geophysical Observatory has carried out an extensive group of theoretical studies on the atmospheric diffusion of impurities from industrial sources [9, 12, etc.]. The characteristics of the propagation of an impurity were studied on the basis of the solution of the turbulent diffusion equation

$$u\frac{\partial q}{\partial x}+w\frac{\partial q}{\partial z}=\frac{\partial}{\partial z}k_z\frac{\partial q}{\partial z}+k_y\frac{\partial^2 q}{\partial y^2}. \qquad (1)$$

Axis x is parallel to the wind, axis y is perpendicular to it in the horizontal plane, axis z is oriented along the vertical, q is the impurity concentration, u is the wind velocity, w is the velocity of ordered displacement of the impurity along the vertical, and k_z and k_y are the vertical and horizontal components of the exchange coefficient.

The initial condition (for x = 0) taken was the presence of a point source of impurity at height z = H, and the boundary conditions taken were the absence of turbulent flow of the impurity on the underlying surface (or the complete absorption of the impurity in the case of a water surface) and a decrease of the concentration to zero at a sufficiently large distance from the source. The thickness of the air layer in which the dispersal of the impurity from major industrial enterprises takes place is very large. In such a layer, the variation of the wind velocity and components of the exchange coefficient with the height is frequently complex in character. For this reason, a sufficiently general solution of equation (1) with the indicated boundary conditions may be obtained only by numerical methods. In addition, it is first necessary to carry out the possible simplifications of the problem, primarily, in accord with the available data and concepts of the parameters and physical mechanisms of the processes studied.

In this connection, it is essential to use the results of [2], according to which the horizontal component of the exchange coefficient k_y changes with the height in proportion to the wind velocity, i.e., $k_y = k_0 u$. In this case

$$q(x,\ y,\ z)=\frac{q'(x,\ z)}{2\sqrt{\pi k_0 x}}e^{-\frac{y^2}{4k_0 x}}. \qquad (2)$$

The quantity q' (x,z) satisfies the equation

$$u\frac{\partial q'}{\partial x'}+w\frac{\partial q'}{\partial z}=\frac{\partial}{\partial z}k_z\frac{\partial q'}{\partial z} \qquad (3)$$

and the initial condition of the presence of a linear source at height z = H. In addition, the same boundary conditions are preserved for q' as for q.

For certain models of the variation of u and k_z with height, equations (1) and (3) were solved analytically [2, 20, 30, 33, etc.]. In [7, 10, 11, 12, etc.], a numerical solution of this problem was obtained. The terms of equation (3) were approximated by finite differences, and the equation thus transformed was solved by means of the difference factorization method, using computers.

In assigning the meteorological parameters u and k_z contained in (1), one must differentiate between normal weather conditions, observed relatively frequently, and abnormal conditions, encountered less frequently but of substantial interest, particularly in cases where they may lead to heavy atmospheric pollution.

Under normal conditions above a relatively flat area, the wind velocity u changes with the height in an approximately logarithmic manner, and the exchange coefficient k_z increases linearly with the height in the ground layer of air and remains approximately constant in the superjacent layer.

$$u = u_1 \frac{\lg z/z_0}{\lg z_1/z_0}; \quad k_z = \begin{cases} \nu + k_1 \frac{z}{z_1} \text{ при } z \leqslant h; \\ \nu + k_1 \frac{h}{z_1} \text{ при } z > h. \end{cases} \tag{4}$$

Here u_1 and k_1 are values of u and k_z for $z = z_1$ (usually $z_1 = 1$ m), z_0 is the roughness of the underlying surface, ν is the coefficient of molecular diffusion for air, and h is the height of the ground layer. As was shown in [10], the consideration of small deviations of u and k_z from (4) is nonessential. In the case of considerable deviations which may take place under abnormal conditions, the solution of the problems by numerical methods proves to be particularly effective.

Usually, the diffusion of a light impurity ($w \approx 0$) and that of a heavy impurity having a definite settling rate are studied separately.

Let us examine the general methods of calculating the parameters of the problem. For a given type of dependence of u and k_z on z, the calculations may be carried out for definite values of u_1 and k_1, and the change to other values of these quantities can be achieved on the basis of similarity considerations. Indeed, if z_0 and h are fixed and one considers that substantial changes in ν have little effect on the results [10], the following relation is valid for the concentration of a light impurity:

$$q = \frac{M}{u_1} \sqrt{\frac{k_1}{k_0 u_1}} \Phi_1 \left(\frac{k_1 x}{u_1}, H, z \right) e^{-\frac{y^2}{4k_0 x}}, \tag{5}$$

where M is the capacity of the source.

Thus, it is sufficient to determine the "standard" function Φ_1 in numerical calculations of increased accuracy for only one pair of values u_1 and k_1 for different H values. Further calculations of the concentration are made on the basis of (5), as is done in the presence of an analytical solution of the problem.

To evaluate the pollution of the ground layer of air, the surface concentration ($z = 0$) is usually employed. Of special practical importance is the determination of q_m, the maximum surface concentration, reached at some distance x_m when $y = 0$. The structure of formula (5) indicates that the maximum on the function q for $y = z = 0$ depends only on H. Thus,

$$q_m = \frac{M}{u_1} \sqrt{\frac{k_1}{k_0 u_1}} \psi_1 (H), \tag{6}$$

and

$$x_m = \frac{u_1}{k_1}\varphi_1(H). \tag{7}$$

Calculations performed in [9] and recently indicate that the functions $x_1(H)$ and $\phi_1(H)$ are adequately approximated by a power function, i.e.,

$$q_m \approx C_1 \frac{M}{u_1}\sqrt{\frac{k_1}{k_0 u_1}}\frac{1}{H^{\beta_1}} \tag{8}$$

and

$$x_m \approx C_2 \frac{u_1}{k_1} H^{1+\beta_2}, \tag{9}$$

where C_i, β_i ($i = 1, 2$) are constants that, as was shown by the calculations, depend relatively little on h and z_0. For $h = 100$ m and $z_0 = 0.01$ m, $\beta_1 \approx 1.9$, $\beta_2 \approx 0.2$.

In the case of a heavy impurity for constant values of w, from an analysis of equation (1) and the initial condition at $x = 0$, similarly to (5) and (6), we obtain

$$q_w = \frac{M}{u_1}\sqrt{\frac{k_1}{k_0 u_1}}\Phi_2\left(\frac{k_1 x}{u_1}, \frac{w}{k_1}, H, z\right)e^{-\frac{y^2}{4k_0 x}}, \tag{10}$$

and for the maximum surface concentration

$$q_{mw} = \frac{M}{u_1}\sqrt{\frac{k_1}{k_0 u_1}}\psi_2\left(H, \frac{w}{k_1}\right). \tag{11}$$

If as was done in [11], the factor $1/H^{\beta_1}$ is separated in ψ_2, as in (8), formula (11) may be transformed to the form

$$q_{mw} = q_m \chi_m\left(H, \frac{w}{k_1}\right), \tag{12}$$

where q_m is defined by formula (6), and χ_m is some function that is found from the results of the calculation.

Similarly we can write that

$$x_{mw} = \frac{u_1}{k_1}\varphi_2\left(H, \frac{w}{k_1}\right) \tag{13}$$

or

$$x_{mw} = x_m \varkappa_m\left(H, \frac{w}{k_1}\right), \tag*{\$14)}$$

where

$$\varkappa_m\left(H, \frac{w}{k_1}\right) < 1.$$

According to (11), in the range of w values from 0 to 0.25 m/sec and H values from 100 to 250 m, χ_m changes from 1 to 2-2.5 and depends on h. Recently, additional calculations were made for a wider range of variation of the initial parameters. It turns out that as w increases, χ_m increases approximately in proportion to w, and the proportionality coefficient is a complex function of H. In analyzing the relationships obtained, it is useful to make use of simpler cases admitting an analytical solution of the problem. Thus, N. Ye. Berlyand's results [2] for a light impurity may be compared with those of L. S. Gandin and R. E. Soloveychik [20] for a heavy impurity. In these results, consideration is given to the case where the exchange coefficient increases indefinitely with the height according to the linear law ($k = k_1 z$) for $u = u_1 z^n$. In this case it turns out that $\chi_m = \chi_m \left(\frac{w}{k_1}\right)$, i.e., χ_m is independent of H. When the components of the exchange coefficient k_y, k_z and the wind velocity u take constant values, the surface concentration of the heavy impurity on axis x from the source at height H (with the condition for z = 0: $k\frac{\partial q}{\partial z} = 0$) is given by the formula

$$q_w|_{y=z=0} = \frac{2M}{\sqrt{\pi}\,\sigma_1 u H^2}\frac{k_z}{k_y} e^{\sigma^2}\left[1 - \sigma_2\sqrt{\sigma_1}\, r(\sigma)\right], \qquad (15)$$

where

$$r(\sigma) = e^{\sigma^2}\operatorname{erfc}(\sigma); \quad \sigma = \frac{1}{\sqrt{\sigma_1}} + \sigma_2\sqrt{\sigma_1};$$

$$\sigma_1 = \frac{4k_z x}{uH^2}; \quad \sigma_2 = \frac{wH}{4k_z}.$$

According to (15), the concentration maximum q_{mw} is determined numerically. Fig. 1 shows the dependence $\chi_m = \frac{q_{mw}}{q_m}$ on σ_2. As is evident from this figure, χ_m increases in approximately linear fashion with $\sigma_2 = \frac{wH}{4k_z}$ ~~over a~~ wide range of variation of the parameters.

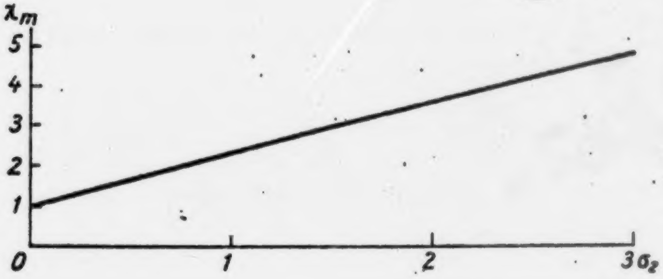

Fig. 1.

When a model for k_z with a "break" is used, according to which $k_z = k_1 h$ for z>h, the analog of σ_2 is the parameter $\frac{wH}{k_1 h}$. Data of calculations for relatively small H values at which the "break" of k_z does not play a substantial part, confirm that χ_m depends little on H, and for greater heights χ_m increases with H. At sufficiently large H (400-500 m) and w (0.2-0.3 m/sec), χ_m reaches 4-5.

The concentration q of both the light and heavy impurity obtained by solving equation (1), which pertains to a steady state, is formally independent of time. However, q is indirectly a function of time, since the coefficients contained in (1) are time-dependent. As was shown in [12], the values of the components of the exchange coefficient k_z and k_y are determined by the action of turbulent eddies of comparatively small size with a characteristic time τ usually of the order of 2-3 min. If the time T to which the concentrations studied are referred is much greater than τ, one should take into consideration the action of larger eddies, which cause fluctuations of the wind direction averaged over the interval τ. Within the framework of the above scheme, k_y and k_z being kept constant in time, this effect may be taken into account by determining the average concentration $\bar{q}$ for the time period T.

On the basis of the above dependence of q on y (5) according to [9 and 12]

$$\bar{q}\big|_{y=0} = q\big|_{y=0} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} e^{-\frac{(y\cos\varphi - x\sin\varphi)^2}{4k_0 x}}\,\omega(\varphi)\,d\varphi. \tag{16}$$

Here $\omega(\phi)$ is the probability of deviation of the wind direction by angle ϕ, and in accordance with the observational data

$$\omega(\varphi) = \frac{1}{\varphi_0\sqrt{2\pi}}\,e^{-\frac{\varphi_2}{2\varphi_0^2}},$$

where ϕ_0 is the dispersion of the wind direction averaged over time τ, in the course of time T.

For sufficiently large χ values it was found in [9] that

$$\bar{q} = \frac{q\big|_{y=0}}{\varphi_0}\sqrt{\frac{2k_0}{x}}\,e^{-\frac{y^2}{2\varphi_0^2 x^2}}. \tag{17}$$

Taking (5) into account, we find that

$$\bar{q}\big|_{y=0} = \frac{Mk_1}{u_1^2\varphi_0}\,\Phi_3\left(\frac{k_1 x}{u_1},\ H,\ z\right). \tag{18}$$

It should be noted that $\bar{q}$ in the case of large χ values is independent of k_0, and the effect of horizontal dispersal shows up in (18) only via the dispersion of the wind direction ϕ_0.

For other χ values, a more accurate expression for $\bar{q}$ is given in [9 and 12].

The formulas obtained permit one to evaluate the dependence of the impurity concentration on the sample intake time *t* in cases involving an experimental determination of the concentration. To this end, the time *t* should be included in the indicated averaging period T, and one should also allow for the duration of the transport of the impurity from the sources to the point of observation at a distance χ. One can approximately set $T=t+\frac{x}{\bar{u}}$, where $\bar{u}$ is the average transport velocity.

The time interval T and hence the time of sample intake t determine first of all the dispersion of the wind direction ϕ_0. As T increases, ϕ_0 rises, and the concentration $\bar{q}$ decreases. At small T values these changes show up more clearly, and at large T values they slow down. The dependence of ϕ_0 on T and on the interior average interval τ and also on the meteorological conditions is described in [21].

In accordance with (18) and with the use of power approximations similar to those contained in formulas (8) and (9), the maximum concentration q_m and distance $\bar{x}_m$ at which it is reached are given by the formulas

$$\bar{q}_m \approx C_3 \frac{Mk_1}{u_1^2\varphi_0} \frac{1}{H^{\beta_3}}, \tag{19}$$

$$\bar{x}_m \approx C_4 \frac{u_1}{k_1} H^{1+\beta_4}. \tag{20}$$

The quantity β_3 amounts to about 2.3-2.5, and β_4 is approximately equal to β_2.

In determining $\bar{q}|_{y=0}$ for $x \neq x_m$ it is expedient to make use of the fact that according to the calculations, $\frac{\bar{q}}{\bar{q}_m}$ is approximately dependent on $\frac{x}{\bar{x}_m}$ only [10].

If long periods of time T*, including periods of many years, are studied, the probability of the wind direction $\Omega(a)$ at angle a (measured clockwise from the north-south direction) is determined by large-scale eddies and usually characterized by the wind rose. The concentration $\bar{\bar{q}}$ average for the period T* at a stationary observation point is then defined by the relation

$$\bar{\bar{q}} = \int_{-\pi}^{\pi} \tilde{\tilde{q}}\,\Omega(\alpha)\,d\alpha. \tag{21}$$

Here $\tilde{\tilde{q}}$ is the concentration $\bar{q}$ calculated according to (17) and averaged for different wind directions over the values of the wind velocity u_1 and exchange coefficient k_1.

It follows from (17) that $\bar{q}$ is different from zero in a comparatively small angular sector within which one can assume that $\Omega(a) = \Omega_a$ = const. Then

$$\bar{\bar{q}} = \sqrt{2\pi}\varphi_0\Omega_a\tilde{\tilde{q}}\big|_{y=0}. \tag{22}$$

By ϕ_0 is meant the average value of this parameter for the given wind direction.

Comparison of (22) and (18) shows that the average concentration is independent of the parameters of horizontal diffusion ϕ_0 and k_0.

If P is the frequency of the winds in the direction of a given rhumb (in fractions of unity), or a total number of rhumbs n, and $P_0 = \frac{1}{n}$ is the frequency of winds of one rhumb for a circular wind rose, then

$$\Omega_\alpha = \frac{P}{P_0 2\pi},$$

$$\bar{\bar{q}} = \frac{P}{P_0} \frac{\varphi_0}{\sqrt{2\pi}} \tilde{q}\Big|_{y=0}. \tag{23}$$

The stack and flue gases coming from the chimneys have a definite exit velocity. In addition, they frequently possess buoyancy, since their initial temperature is higher than that of the surrounding air. Thus, in the vicinity of the discharge source there is created a field of vertical velocities that occasionally extends over large distances, these velocities decreasing with the distance from the source, which promotes the ascent of the impurity. The problem therefore arises of finding the field of displacement velocities of air near the source in order to allow for it in solving equation (1). Because of the complexity of this problem, due to the nonlinearity of the equations describing the propagation of the overheated jet in the driving stream, it is usually solved with considerable simplifying assumptions. The initial ascent of the impurity is considered for the most part in the absence of the horizontal wind velocity and with some other assumptions. It is assumed that at a certain height above the stack the vertical velocities are low, and as was mentioned above, the concept of an effective ascent of the smoke jet ΔH above the mouths of the stacks is introduced.

The paper [12] points to the drawbacks of such an approach and formulates a more general statement of the problem for an overheated jet in a driving turbulent flow. Here the propagation of the impurity along axis y is approximately described by a relation of type (2), and the determination of the horizontal and vertical velocity components u and w is done by solving the following system of equations:

equation of motion

$$u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z} = \frac{\partial}{\partial z} k_z \frac{\partial w}{\partial z} + \frac{g\vartheta}{T_e};$$

equation of heat influx

$$u\frac{\partial \vartheta}{\partial x} + w\frac{\partial \vartheta}{\partial z} = \frac{\partial}{\partial z} k_z \frac{\partial \vartheta}{\partial z};$$

equation of continuity

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{24}$$

for suitable boundary conditions. Here ϑ is the difference between the temperature of the jet and that of the surrounding air, T_e is the temperature of the surrounding air (^{0}K), and g is the acceleration due to gravity.

The solution of system (24) together with diffusion equation (1) is carried out numerically according to the scheme given in [12].

The paper [9] gives a formula for calculating ΔH, approximately obtained from theoretical considerations

$$\Delta H = 1{,}5\,\frac{w_0 R_0}{u}\left(2{,}5 + 3{,}3\,\frac{q R_0 \Delta T}{T_e u^2}\right), \tag{25}$$

where u is the wind velocity at the height of the vane, w_0 is the initial exit velocity of the gases, and ΔT is the difference between the temperature of the exiting gases and that of the atmosphere at the level of the stack orifice.

The quantity $\bar{q}_m$ substantially depends on the meteorological conditions, according to the parameters contained in (19) and (25). Of particular importance is the dependence of $\bar{q}_m$ on the wind velocity u. On the one hand, at a fixed height of the source, $\bar{q}_m$ increases with decreasing wind velocity at height $z_1 = 1$ m (the transition from u_1 to u at the vane height z_v is achieved in accordance with (4)). On the other hand, as the wind velocity u decreases at sufficiently small values of u, the effective source height $H_e = H + \Delta H$ increases rapidly by virtue of (25). Therefore, each case has some "unsafe" wind velocity u_M at which the highest concentration $\bar{q}_m$. is reached. The value of u_M is determined from the condition

$$\frac{\partial \bar{q}_m}{\partial u} = 0. \tag{26}$$

In the general case, when analyzing the influence of the wind velocity u on $\bar{q}_m$ it is also necessary to consider the dependence on u of the coefficients contained in (19), in particular, the quantity $\frac{k_1}{u_1 \varphi_0}$. It is known ([15] etc.) that $\frac{k_1}{u_1}$ depends on the number $B = \frac{\delta T}{u_1^2}$, where δT is the temperature difference at two levels in the ground layer of air (usually 0.5 and 2 m). The quantity ϕ_0 also depends on B [21]. In the case of unstable stratification (δT>0), $\frac{k_1}{u_1}$ and δ_0 increase with B; in a stable stratification (δT<0), $\frac{k_1}{u_1}$ decreases with increasing absolute value of B, while ϕ_0 has a tendency to increase. The values of ϕ_0 reach a certain minimum under close to equilibrium conditions. Thus, the ratio $\frac{k_1}{u_1 \varphi_0}$ decreases with a reinforcement of stability in the presence of a stable inversion stratification and, in general, is less than in an unstable state of the atmosphere. Consequently, other things being equal, the impurity concentration (by virtue of its proportionality to $\frac{k_1}{u_1 \varphi_0}$) in a superadiabatic temperature gradient is greater than in an inversion gradient.

In an unstable stratification, excluding the case of slight winds (up to 1-2 m/sec), the quantity $\frac{k_1}{u_1\varphi_0}$ depends relatively little on the wind velocity u and increases slightly with increasing B. It may be approximately assumed that $\frac{k_1}{u_1\varphi_0}$ is independent of u_1. Taking this assumption into account and assuming that $\beta_3 = 2.3$ and $\beta_4 = 0.2$, we can obtain the following equation for u_M from (19), (25) and (26):

$$\left(\frac{v_{\text{м}}}{u_{\text{м}}}\right)^3 + 0{,}39\left(\frac{v_{\text{м}}}{u_{\text{м}}}\right)\sqrt[3]{f} - 1 = 0, \tag{27}$$

where for convenience of presentation, the following notation has been introduced:

$$v_{\text{м}} = 0{,}65\sqrt[3]{\frac{V_1\Delta T}{H}}; \quad f = 10^3\frac{w_0^2 D}{H^2\Delta T}. \tag{28}$$

Here $D = 2R_0$ is the diameter of the stack orifice and $\overline{V}_1 = \frac{\pi D^2 w_0}{4}$ is the volume of the gases exiting from the stack.

From the solution of equation (27) it follows that

$$u_{\text{м}} = \frac{v_{\text{м}}}{G_1(f)}, \tag{29}$$

then

$$\overline{q}_m\big|_{u=u_{\text{м}}} = \frac{C_3 \lg\frac{z_\Phi}{z_0}}{0{,}65\lg\frac{z_1}{z_0}}\left(\frac{k_1}{u_1\varphi_0}\right)_{u=u_{\text{м}}}\frac{M}{H^2\sqrt[3]{V_1\Delta T}}G_2(f); \tag{30}$$

$$\overline{x}_m\big|_{u=u_{\text{м}}} = C_4\left(\frac{u_1}{k_1}\right)_{u=u_{\text{м}}} H^{1,2}G_3(f), \tag{31}$$

where

$$\begin{gathered} G_1(f) \approx 1 - 0{,}13\sqrt[3]{f}; \\ G_2(f) = \frac{G_1(f)}{\left[1 + 0{,}30\sqrt[3]{f}\,G_1(f) + 0{,}17G_1^3(f)\right]^{2,3}}; \\ G_3(f) = \left[1 + 0{,}30\sqrt[3]{f}\,G_1(f) + 0{,}17G_1^3(f)\right]^{1,2}. \end{gathered} \tag{32}$$

For the case in which the wind velocity $u \neq u_m$, for the highest concentration $\overline{q}_{mu}$ and distance $\overline{x}_{mu}$ at which it is reached, the following formulas can be written down on the basis of (19), (25) and (29):

$$\overline{q}_{mu} = \overline{q}_m\big|_{u=u_{\text{м}}}r; \quad \overline{x}_{mu} = \overline{x}_m\big|_{u=u_{\text{м}}}p, \tag{33}$$

where

$$r = \frac{v_{\text{м}}}{u\,G_1(f)}\left[\frac{1 + 0{,}30\sqrt[3]{f}\,G_1(f) + 0{,}17G_1^3(f)}{1 + 0{,}30\sqrt[3]{f}\left(\frac{v_{\text{м}}}{u}\right) + 0{,}17\left(\frac{v_{\text{м}}}{u}\right)}\right]^{2,3};$$

$$p = \frac{\left(\frac{u_1}{k_1}\right)_{u\neq u_{\text{м}}}}{\left(\frac{u_1}{k_1}\right)_{u=u_{\text{м}}}}\left[\frac{1 + 0{,}30\sqrt[3]{f}\left(\frac{v_{\text{м}}}{u}\right) + 0{,}17\left(\frac{v_{\text{м}}}{u}\right)^3}{1 + 0{,}30\sqrt[3]{f}\,G_1(f) + 0{,}17G_1^3(f)}\right]^{1,2}.$$

The use of numerical methods of solution of the problem made it possible to study the above-indicated anomalous conditions and also the problem of propagation of the impurity over a dissected topography. These results have been presented in sufficient detail in [10, 12, 13, and 14], and we shall consider below only some conclusions of practical importance.

3. Practical Recommendations

In designing industrial enterprises it is important to determine the highest possible impurity concentration, since, in order to meet the sanitary requirements, it must not exceed the permissible value. In order to find this value (excluding anomalous conditions, which will be discussed later), in (30) it is necessary to take $\frac{k_1}{u_1\varphi_0}$ for unfavorable meteorological conditions, in particular, for an unsafe wind velocity and stratification for which $\bar{q}_m|_{u=u_M}$ will reach the highest value q_M.

The working formula for determining the highest concentration q_M can be given in the following form:

$$q_M = \frac{AMmF}{H^2\sqrt[3]{V_1 \Delta T}}, \tag{34}$$

where

$$A = a\frac{k_1}{u_1\varphi_0}; \quad m = \frac{G_2(f)}{G_2(f_0)}. \tag{35}$$

The coefficient m is determined from the graph of Fig. 2; it is normalized so that for $f = f_0 = 0.42$ m/sec^2 deg, m = 1. The adopted value of f_0 corresponds to the frequently occurring discharge parameters H, w_0, D and ΔT for major industrial and power facilities (for example, H = 120 m, D = 6 m, w_0 = 10 m/sec, ΔT = 100°).

The coefficient F determines the influence of the settling rate of a heavy impurity and is found via the function χ_m, allowing for the density and the characteristic particle size distribution. The distributions of the dispersity of the dust and ash may be quite different. They depend on the efficiency and type of the dust and ash catchers. The estimates performed showed that for practical calculations one can approximately assume F = 2 if the efficiency of the purification is above 90%, and F = 2.5 for a lower degree of purification. These values pertain to cases where wH does not exceed 100 m^2/sec, i.e., for average settling rates of the particles they apply to stacks whose height does not exceed 250-300 m. At higher settling rates of the particles, this condition may fail to be fulfilled for lower stacks as well. The quantity w increases with the size and density of the dust particles. It should be kept in mind that as a rule, the density of the dust is below the density of the substance of which it is constituted, since the structure of dust particles frequently consists of loose conglomerates. Their density is usually close to 1 g/cm^3, but in some cases reaches 3-4 g/cm^3 and more.

The coefficient A is taken for unfavorable meteorological conditions usually observed in the daytime in summer in the presence of a highly developed turbulent exchange.

The value of the parameter a entering into the coefficient A depends to some extent on the roughness of the underlying surface z_0 and on the height of the ground layer h; the latter is taken such that q_M reaches its highest values [9]. For a medium roughness for the conditions of a flat area, a is approximately equal to 0.3.

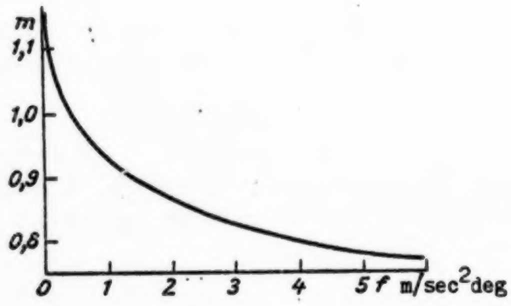

Fig. 2.

According to the observations in the area of the Shchekino State Regional Electric Power Plant (SREPP), on the average, A = 120 if it is assumed in (34) that q is expressed in mg/m^3, M in g/sec, N in m, v in m^3/sec, and ΔT in °C. This value of A may be assigned to areas with a flat or moderately dissected topography in the central part of the European territory of the USSR and in other regions with similar climatic conditions. As was noted in [9], it may be postulated that in the southern regions of the USSR and in forested regions characterized by a marked vertical turbulent exchange in the atmosphere, A amounts to approximately 200.

In regions where the conditions of turbulent exchange are intermediate in character, A is taken equal to 160. Expeditionary studies carried out in the vicinity of the Suvorovo and Moldavian SREPP in Leningrad, Cherkassy, Krasnoyarsk, Balakovo, and other regions confirmed the validity of these results. In determining the coefficients A, data on the distribution of the rate of turbulent exchange over the territory in the daytime in summer were used [26]. It was assumed that in regions with high average values of $\frac{k_1}{u_1}$ (which correspond to large average B), the average concentrations of noxious substances would increase in accordance with formulas (18) and (23). The values of the coefficients A for different regions of the USSR are given in [43].

According to (29), the unsafe velocity u_M is found approximately from the formula

$$u_м \approx 0{,}65 \sqrt[3]{\frac{V_1 \Delta T}{H}}\,. \qquad (36)$$

The distance x_M at which the maximum concentration q_M is attained is determined in accordance with formula (31) by selecting the parameters it contains for unfavorable conditions. The calculations show that, basically, $x_M = (20\text{-}25)\ H$. In addition, the ratio $\frac{x_{\text{м}}}{H}$ depends to some extent on H, it is smaller for low stacks and greater for high ones. The ratio $\frac{x_{\text{м}}}{H}$ also depends to some extent on the quantity $\frac{k_1}{u_1}$, determined at the unsafe wind velocity u_M and for conditions of highly developed turbulence. As u_M decreases, $\frac{k_1}{u_1}$ usually increases, and therefore $\frac{x_{\text{м}}}{H}$ will be somewhat less, but for practical purposes a detailed calculation of x_M is not necessary and it is sufficient to confine oneself to the approximate relation

$$x_{\text{м}} \approx 20H. \tag{37}$$

It should be kept in mind that concentrations of noxious substances differing from the maximum concentration q_M by no more than 30% are observed at distances of (10-40) H.

From formulas (33), allowing for (36) and the above-mentioned dependence of the meteorological parameters on the wind velocity under unsafe conditions, we shall obtain formulas for the highest concentration q_{Mu} with u unequal to u_M and for the distance x_{Mu} at which this concentration is reached,

$$q_{\text{м}u} = q_{\text{м}} r; \quad x_{\text{м}u} = x_{\text{м}} p. \tag{38}$$

The quantities r and p depend chiefly on $\frac{u}{u_{\text{м}}}$, which permits the plotting of convenient working graphs (Fig. 3). The graph for r shows that the dependence of the concentration maximum q_{Mu} on the wind velocity u is asymmetrical in character. For $u<u_M$, q_{Mu} increases rapidly with u, and for $u>u_M$, the decrease of q_{Mu} is slower. Analysis of the variation of the coefficient p shows that, at wind velocities u substantially lower than u_M, the maximum concentrations q_{Mu} are observed at distances several times greater than $x_M = 20$ H. At wind velocities u much greater than u_M, the quantities q_{Mu} are observed at distances equal to approximately 15 H.

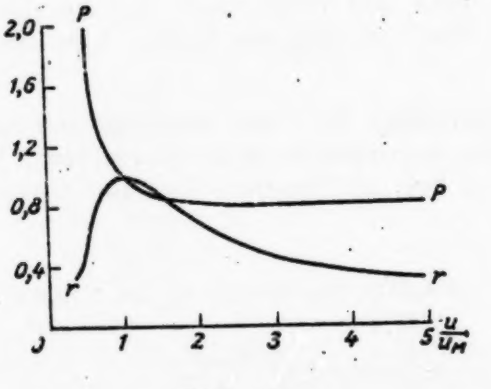

Fig. 3.

Calculations performed in [10] showed that for the usual effective source heights (excepting the cases of slight winds) one can approximately assume $\frac{q}{q_м}$ to be a function of $\frac{x}{x_м}$, and $\frac{q}{q_{мu}}$ to be a function of $\frac{x}{x_{мu}}$. It follows that the surface concentration q on the axis of the smoke plume (at y = 0) is given by the formulas

$$q = q_м s_1 \text{ при } u = u_м; \quad q = q_{мu} s_1 \text{ при } u \neq u_м. \tag{39}$$

For a gaseous mixture, s_1 is determined from the quantity $\frac{x}{x_м}\left(\frac{x}{x_{мu}}\right)$ by means of the solid curve of the graph (Fig. 4).

For dust at $\frac{x}{x_м}\left(\frac{x}{x_{мu}}\right)$ values less than 2, a solid curve can also be used for practical calculations. At larger x values a faster decrease of the concentration of a heavy impurity with distance is substantially manifested, whereas for the usually observed dispersity of the discharges, the dashed line in this figure should be employed.

In accordance with formula (5) and the above-indicated results, the highest concentration q_y for $y \neq 0$ is determined from q for y = 0 by means of the formula

$$q_y = q s_2 \tag{40}$$

where s_2 is a function of $\frac{y}{x}$ and is found from the graph (Fig. 5).

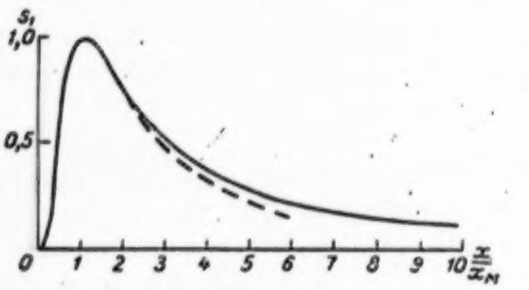

Fig. 4.

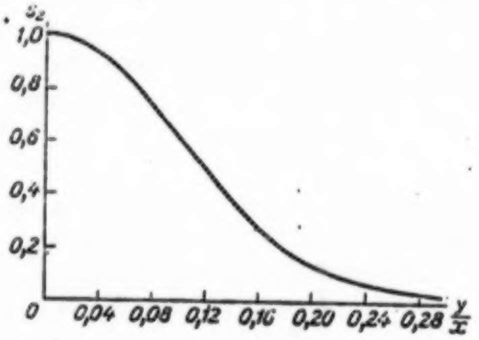

Fig. 5.

An evaluation of the danger of atmospheric pollution from the calculated values of the concentration is made by comparing them with the maximum permissible concentrations (MPC). At the present time, hygienists [36] accept two forms of MPC for air in populated areas, the maximum single concentration (MPC_s) and the mean daily concentration (MPC_d). The former refers mainly to a 20-30 minute time interval. It defines the hazard of a short-term action of a given impurity ingredient on the human body. The value of MPC_d indicates the permissible degree of pollution of air in the course of a long period, without strict specification of its duration. It is usually established on the basis of experiments in so-called "inoculation" chambers where the concentrations are determined at which, independently of the time spent by animals in the chamber, the investigated impurities have no appreciable effect on them.

The above formulas (with the indicated values of coefficient A) are used to determine the single concentrations that should be compared with MPC_s and with the single concentrations obtained from observations. When it is necessary to calculate single concentrations for shorter time intervals, the above-mentioned methods [9, 12] can be used.

To use MPC_d, two alternatives are possible. In the first, the calculation is made only for cases of wind directions that are very stable in the course of 24 hours or longer. In so doing, it is necessary to anticipate a set of measures such that the calculated concentrations do not exceed MPC_d. In this case, the average daily concentrations will be closest to the single concentrations, but such conditions are observed very seldom and their discussion is of no practical significance.

It is more logical to relate the concept of mean daily MPC to a regime established in the course of a period of many years. In this case, the name "mean daily MPC" has an arbitrary meaning. Accordingly, the calculated concentration should be determined for points that are fixed in the area, allowing for the climatological data on the atmospheric diffusion parameters - the wind velocity and direction and the coefficient of vertical turbulent exchange. It will be shown that at the present time such an approach involves a definite contradiction between the recommended values of single and average daily MPC's. Indeed, we shall use the relation (23) obtained above between the single concentration q and average concentration $\bar{\bar{q}}$. For the evaluations we shall assume that $\tilde{\bar{q}} = q$ and that the wind rose is circular, i.e., $\frac{P}{P_0} = 1$. Then $\bar{\bar{q}} = \frac{\varphi_0}{\sqrt{2\pi}} \bar{q}$. For $\phi_0 = 0.1$, we have $\frac{\bar{\bar{q}}}{\bar{q}} \approx \frac{1}{25}$.

If we consider that the unsafe wind velocities and the intense turbulent exchange are not observed during the entire period, the averaging should be carried out over the possible values of the wind velocity and exchange coefficient, i.e., it should be assumed that $\tilde{\bar{q}}$ is always less than $\bar{q}_1$ and $\frac{\bar{\bar{q}}}{\bar{q}}$ is less than $\frac{1}{25}$. According to the experimental data of Chamberlain [47] and some other authors, $\frac{\bar{\bar{q}}}{\bar{q}} \approx \frac{1}{40}$. Therefore, in order to obtain consistent results in determining the permissible discharge, the necessary stack height, etc. when calculated data are used, the ratio $\frac{MPC_s}{MPC_d}$ should also be no less than $\frac{1}{25}$ - $\frac{1}{40}$. In the tables for MPC [36], the ratio $\frac{MPC_s}{MPC_d}$ ranges mainly from $\frac{1}{3}$ to 1. For this reason, the requirement $q_M \leqslant MPC_s$ turns out to be a considerably stricter condition than the requirement that the average concentration for many years be less than MPC_d.

Taking the planning experience into account, one must admit that the use of single concentrations in the calculations permits the achievement of the necessary atmospheric purity in more real terms. Therefore, it appears necessary at the present time to use single concentrations as the base. Thus, in designing and operating industrial enterprises the following condition should be fulfilled

$$q_{м} \leqslant \mathrm{MPC_s} \tag{41}$$

It then follows from formula (34) that the minimum stack height of a single source is given by

$$H = \sqrt{\frac{AMmF}{\mathrm{MPC}\sqrt[3]{V\Delta T}}}. \tag{42}$$

Since m depends on f and f on H, calculations using formula (42) should be carried out by successive approximations, setting first m = 1. Two to three approximations are usually sufficient.

Let us now consider the case of a group of sources, when the calculation is made on the basis of a superposition of concentration fields from individual sources. Analysis of the above formulas indicates that if the distance between the stacks does not exceed their average height by a factor of more than 3-4, the sources may be treated as being located at a single point. If at the same time the discharge is distributed uniformly among N stacks of identical height and diameter, the total concentration will be given by the formula

$$q_{м} = \frac{AMmF}{H^2}\sqrt[3]{\frac{N}{V\,\Delta T}}. \tag{43}$$

where M is the total discharge from all the stacks and $V = \frac{\pi D^2 w_0 N}{4}$ is the total volume of stack gases.

Accordingly, it follows from (36) that

$$u_{м} = 0{,}65\sqrt[3]{\frac{V\,\Delta T}{NH}}. \tag{44}$$

For sources with different unsafe wind velocities, the calculations are simplified if one introduces into the discussion the weighted-mean unsafe wind velocity u_{Mw}

$$u_{Mw} = \frac{\sum\limits_{i=1}^{N} u_{мi} q_{мi}}{\sum\limits_{i=1}^{N} q_{мi}}, \tag{45}$$

where u_{Mi} and q_{Mi} are the values of the unsafe velocity and highest concentration for the i-th source, and N is the total number of sources.

The calculations performed showed that in this case it is practically sufficient at first to determine for each source the highest concentration q_{Mu} and distance x_{Mu} at which this concentration is reached at a wind velocity

$u = u_{Mw}$. Then, if the sources are located close to each other or are grouped along a certain line, the distribution of concentration from the sum of the sources is found by graphical summation. The highest concentration value taken is q_M, and the distance from some arbitrary origin of coordinates is taken as x_M.

In the general case, when the sources cannot be reduced to a point or a straight line, one has to sum up the fields of the concentration from individual sources by considering its distribution both along the wind and in the direction at right angles to the wind. Obviously, the different wind directions must be considered, since the relative position of the sources changes as a function of these directions, and the concentrations produced by the latter add up in different ways. It is understandable that such calculations become very cumbersome even for a relatively small number of sources. They can be simplified because the concentrations perpendicular to the wind direction decrease much faster than those in the direction parallel to the wind. Experience with the calculations showed that in order to determine the highest total concentration it is sufficient to consider only those directions that pass through pairs of main sources. At the same time, in each direction it is first necessary to carry out the calculations at points corresponding to the maxima of concentrations from the largest sources. A program for the "Ural-4" computer was written for a large number of sources in accordance with the scheme presented above. According to the program, the print-out consists of the maximum total concentration with the characteristics of the conditions under which it is observed, and also the contribution of individual sources to this maximum. The availability of such a program considerably simplifies the selection of the most effective variants of arrangement of the sources and their parameters in planning major facilities, permits plotting of the total fields of concentrations for all of the sources in a city, etc.

In planning new enterprises discharging noxious impurities in areas where the air is already polluted by the same substances from other industrial enterprises, and also in expanding the operating enterprises, in addition to the increase of discharges into the atmosphere, the initial or background concentration q_b should be taken into consideration. In this case, the sum $q_M + q_b$ should not exceed the MPC. The background concentration q_b can be determined by means of the above methods of calculation for a group of sources.

An important problem in the practical application of the results presented above is the determination of the boundaries of the sanitary protective zone (SPZ), i.e., the allowed difference between enterprises discharging noxious substances into the atmosphere and residential areas. Thus far, the problem of the SPZ has essentially been solved empirically. On the basis of the experience of sanitation surveys, a model classification of industrial facilities has been established for the size and the required gap between the enterprises and residential districts [37]. The data on which this classification is based mostly fail to reflect the modern tendency to discharge the bulk of noxious substances through high smokestacks and air ducts. Analysis shows that this classification considers chiefly the pollution of areas close to the enterprises, which is caused by random discharges (i.e., outside stacks). Therefore, the width l_0 of a sanitary protective zone (SPZ) which has now been established is useful when, according to the calculations, the concentration q_M from orderly discharges is less than the MPC, since the method discussed above does not allow for random discharges. However, the width of the SPZ for different classes of enterprises was established primarily for conditions when there is no marked prevalence of winds of definite directions. Under conditions where the mean annual wind rose differs substantially from circular, namely, for a frequency P of winds of certain directions which is greater than the mean value P_0, the width of the SPZ should be corrected by taking into account the characteristics of the wind regime of the area under consideration. For these wind directions, taking into account the above dependence of the average concentration on the frequency of the wind direction P [23], the width of the gap l from the enterprises to the outer limits of the SPZ is given by the formula

$$l = l_0 \frac{P}{P_0}, \qquad (46)$$

and in the directions for which the wind frequency $P<P_0$, $l = l_0$ should be taken.

In cases where, on the basis of calculations in accordance with the above scheme, q>MPC up to a distance L_0 exceeding l_0, the distance l from the pollution source to the outer limits of the SPZ should be greater than l_0. To calculate the distance l it is necessary to consider the characteristics of the distribution of average concentrations in accordance with formula (23). In addition, it is necessary to take into account the study of the nature of the decrease of single concentrations with the distance x for $x>x_M$ (cf., for example, Fig. 4). It follows from Fig. 4 that at these distances, as x increases, the concentration q decreases in approximately inverse proportion to x. Including in the sanitary protective zone a territory with approximately the same average concentrations, one can roughly assume that

$$l = L_0 \frac{P}{P_0} \text{ при } P > P_0 \qquad (47)$$

in the directions for which $P<P_0$ it is necessary to assume that $l = L_0$.

In practical calculations of the degree of pollution of the atmosphere by industrial discharges, of major importance is the consideration of the anomalous conditions mentioned above, and the discussion of some special cases of the propagation of the impurity in the atmosphere. In this connection, of great importance are the results obtained in [8, 10], etc., pertaining to the influence of elevated inversions hindering the transport of the impurity upward. A numerical study showed that in cases where an inversion layer with an attenuated turbulence is located immediately above the source, and a vigorous turbulent exchange takes place below the source, the maximum concentration of a light impurity is sometimes more than doubled. In cases where the inversion layer is located at a height of 100-200 m above the source, the concentration increases to a lesser degree. The presence of elevated inversions may cause a considerably greater effect with cold discharges because of the limitation of their initial ascent [4]. Under these conditions, the effective ascent ΔH cannot exceed a definite limit independently of the decrease of the wind velocity u, the values of the unsafe velocity decrease, and the surface concentrations rise sharply. Despite a marked influence of elevated inversions on the distribution of the impurity concentrations, it should be kept in mind that in many geographical areas they are observed for a comparatively short period of time. For this reason, it was proposed above that the stack height and other discharge parameters be determined from relatively frequent unsafe weather conditions. During periods of elevated inversions, however, particularly when a thick inversion of several hundred meters with average temperature gradients of approximately 3-4° per 100 m is located above the stacks, and the wind is directed from the sources of pollution toward residential areas, a relatively short term decrease of the output of the enterprises should be recommended in order to reduce the discharges into the atmosphere. This is economically more expedient than a sharp increase of the stack height during construction. In some cases it is also necessary to consider possible deviations in the vertical profile of the wind from the logarithmic distribution. Calculations made in [12] have shown that the presence of still layers around the underlying surface, provided there is a well developed turbulence (convection), may also lead to a considerable increase (double or more) of the surface concentrations, this increase being greater the thicker these layers are.

The propagation of the concentration from the source in the presence of a fog changes substantially. The important effect of the increase of the surface concentrations in this case was pointed out in [13]. It turns out that in addition to a redistribution of the impurities because of their absorption from the air by droplets, in the fog layer the concentrations increase because of an additional transport of the impurities from layers of air located above the fog. As sulfur dioxide and some other ingredients dissolve in the fog, their toxicity increases. It should also be noted that fogs are frequently associated with inversion and still conditions that may cause a mutual reinforcement of dangerous effects.

Under dissected topography conditions, air movements arise that result in substantial concentration changes. According to theoretical studies [12, 14], it turns out that under such conditions, the concentration maximum is higher than on a flat topography. For a height of irregularities of 50-100 m with a slope angle of about 5-6°, the difference in the concentration maxima, depending on the location of the source in different forms of the relief, amounts to 50% or more. An increase of the concentration is sometimes observed even when the stacks are located in high areas, in the vicinity of leeward slopes, since here the wind velocities decrease and descending currents arise. On the other hand, in the case of gentle slopes of the relief (the slope angles for the most part do not exceed a few degrees), the air flow around them is practically complete and the increase of the concentration is slight. The influence of a hilly relief on the distribution of concentration manifests itself in areas where the wind velocity changes appreciably at a fixed height. In this connection, a major importance is assumed by a microclimatic study of the area, analogous to the one discussed in [31, 39]. Considerable possibilities are offered by experimental work involving wind tunnel simulation of air streams in complex forms of the relief, under urban conditions, etc. [23, 29].

4. Experimental Verification

The above conclusions from theoretical investigations have been confirmed with extensive experimental material.

One of the first most complete sets of experimental studies of atmospheric pollution by industrial discharges was completed in the region of the Shchekino SREPP. The work was done in 1962-1965 during periods in different seasons of the year and covering a broad range of variations in meteorological conditions. Results of a comparison of the calculated and experimental data obtained were given in [9, 25, 35]. They were shown to agree within 20-30% in terms of the concentrations q_M and character of the dependence of the highest concentrations q on the distances to the source x and on the wind velocities u. The observations confirmed the calculated values of the unsafe wind velocity, which amounts to about 5 m/sec, the general character of the dependence of pollution on the stability of the ground layers of the atmosphere, and also the validity of formula (25) for the magnitude of the initial ascent of the smoke plume.

Similar expeditionary studies by the Main Geophysical Observatory in cooperation with the Moscow Scientific Research Institute of Hygiene and other organizations were carried out during the summer-autumn season in the area of the Cherepet' (1964) and Moldavian SREPP (1965) and also in the region of the Nevskiy chemical plant. In these expeditions, the concentrations of noxious substances were measured at several points located at various distances, including considerable distances, from the source, and the discharge of noxious substances, volume, velocity and temperature of the escaping gases were simultaneously determined. The meteorological observations included gradient measurements of the temperature and velocity of the wind, and aerological measurements of the distribution of these elements and characteristics necessary for calculating the turbulent exchange coefficient in the boundary layer of the atmosphere were also carried out. Photographs of the smoke plume were taken and its parameters were determined visually both from the ground and from observations in an airplane and helicopter.

For the Cherepet' SREPP, whose main discharge takes place from three stacks 140 m high, the calculated concentration maxima q_M were 4.2 mg/m^3 for ash and 1.4 mg/m^3 for sulfur dioxide, and the corresponding experimental q_M values were 3.7 mg/m^3 and 1.8 mg/m^3. The calculated and experimental data on the unsafe wind velocity differed by no more than 1 m/sec.

A characteristic feature of the Moldavian SREPP was the discharge of the impurity through a single stack of 180 m (one of the highest in the USSR at that time) under conditions of a highly developed convection characteristic of the south of the European territory of the USSR. Since wet ash purification was used, the overheating of the stack gases was approximately 40°C, which was substantially below that of the Shchekino and Cherepet' SREPP, where it reached 100-150°C. According to the results given in [22], the calculated values of q_M for sulfur dioxide were 0.26 mg/m^3, and the unsafe velocity $u_M = 2.5$ m/sec; from experimental data, $q_M = 0.3$ mg/m^3 and $u_M = 2-3$ m/sec. A satisfactory agreement was also noted in the distribution of the concentration q with the distance x. The zone of highest concentrations was observed at a distance of 3-4 km from the stacks, which corresponds to the results of the calculations.

In order to study the distribution of impurities pouring into the atmosphere at relatively low temperatures, observations were made in the region of the Nevskiy Chemical Plant. From plant stacks 100 m high, nitrogen oxides were discharged with a temperature contrast of only 15-20°C relative to the ambient air. According to experimental data [24], $q_M = 0.17$ mg/m^3, and according to calculations, $q_M = 0.20$ mg/m^3, and the unsafe velocities in these cases decrease compared to those cited above and amount to 1-2 m/sec according to calculations as well as observations.

On the basis of observational data on the smoke plume from the Nevskiy plant and from the stacks of the Cherepet' and Moldavian SREPP, a satisfactory agreement was noted between the calculated and observed initial ascents of the smoke plume.

A series of theoretical conclusions have been confirmed by experimental studies of the discharge of aerosols from specially constructed high sources. They include experiments on the dumping of heavy fluorescent particles from a 300-meter meteorological mast in the city of Obninsk [17]. Analysis of these experiments showed a good agreement between the calculations and experiments on settling of the impurity on the underlying surface. It was found from both theoretical and experimental data that under convective conditions, the propagation of the impurity depends relatively slightly on the settling rates of the particles, and that the role of gravity settling increases substantially in a stable stratification. Experiments on spraying of a liquid aerosol from heights of 100 to 400 m were analyzed in [28]. In the majority of experiments, confirmation of the theory by experimental data was obtained with respect both to the values of the maximum precipitation of the liquid and to the distances where they were observed. In the great majority of cases, the differences did not exceed 30% of the calculated values. The data given in [17 and 28] on the determination of the turbulent characteristics k_1 and ϕ_0 as the result of solution of the reverse diffusion problem are in accord with the results of gradient and fluctuation observations.

In order to confirm the theoretical conclusions, in addition to the indicated data of observations in the area of the Shchekino SREPP, use was also made in [35] of data obtained from a survey of seven heat and power plants with stack heights of 40 to 150 m, made by the Moscow Scientific Research Institute of Hygiene from 1953 to 1958. This confirmed both the calculated values of the concentration maximum and their dependence on the stack height.

In 1963-1965, a number of public health organizations carried out a comprehensive cycle of surveys of atmospheric pollution around heat and power plants located in various climatic zones of the USSR. This material was presented to the Main Geophysical Observatory for analysis by the Sanitary Epidemiological Administration of the Ministry of Public Health of the USSR. Some results of its treatment and comparisons with the preceding formulas will be cited.

The concentrations of sulfur dioxide and ash around the Pridneprovskaya SREPP with stack heights of 100-120 m were determined by the Ukrainian Institute of Communal Hygiene in 1963. Fig. 6 shows the distribution of highest concentrations obtained versus the distance based on experimental and calculated data.

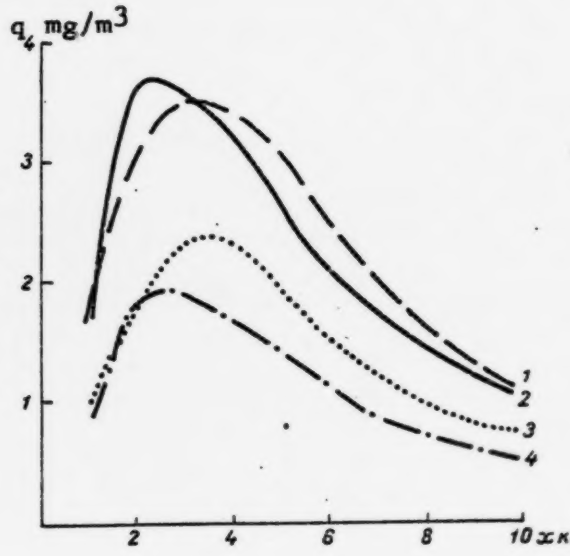

Fig. 6.

Highest concentrations of sulfur dioxide and dust at various distances from the Pridneprovskaya SREPP.

1 - measured dust concentrations, 2 - calculated ash concentrations, 3 - measured sulfur dioxide concentrations, 4 - calculated sulfur dioxide concentrations.

According to the results of the survey of the Serov SREPP with stacks 120 m high, carried out in 1963 by the Sverdlovsk Institute of Labor Hygiene and Professional Diseases, it was found that q_M for sulfur dioxide amounts to 0.26 mg/m^3, and for ash 4.5 mg/m^3; according to calculations, these values are 0.25 and 4.4 mg/m^3, respectively.

The Novosibirsk Scientific Research Sanitation Institute carried out a survey of the Kemerovo SREPP; for sulfur dioxide it was found that $q_M = 3.2$ mg/m^3, and according to calculations, $q_M = 3.0$ mg/m^3.

Data of surveys of a number of other SREPP and heat and power plants (HPP) were used to compile Table 1, which lists experimental and calculated values of q_M for sulfur dioxide. It should be noted that these experimental data are not complete; in particular, the number of samples taken was small, but a definite agreement between them and the calculated values can be seen.

In many cases, agreement also exists for the dust concentrations. However, these data are not cited here, since the available information on the efficiency of the ash catchers was not always reliable and was chiefly based on specifications rather than factual data.

According to Tomson's data [42] pertaining to a Baltic SREPP with a height of 150 m, the highest measured concentration of sulfur dioxide $q_M = 0.4$ mg/m^3, and the concentration calculated by means of the above formula $q_M = 0.6$ mg/m^3.

Table 1

Name	Stack height, m	q_M mg/m^3	
		Experimental	Calculated
Minsk HPP	100	0.22	0.29
Tallinn HPP	104	less than MPC	0.16
Bobruysk HPP	65	Traces	0.1
Alma Ata SREPP	60	Traces	0.27
Karaganda SREPP	70-100	0.6	1.0
Daugavpils HPP	-	Traces	0.8

On the basis of the indicated data for heat and power plants, a graph of $\frac{q_M}{M}$ vs. H was plotted separately for sulfur dioxide (Fig. 7 a) and ash (Fig. 7 b). As is evident from the figure, despite a certain inhomogeneity of the material used, the experimental data confirmed the theoretical conclusions quite well.

In order to check the results of the calculation on a broader class of sources, a comparison was made of the calculated and experimental data on atmospheric pollution by a number of enterprises of the ferrous and nonferrous metallurgy. In particular, use was made of the observational data of the Moscow Scientific Research Institute of Hygiene for October 1962 in the area of the Chelyabinsk Metallurgical Plant. Fig. 8 shows the distribution of sulfur dioxide concentration as a function of the distance to the plant based on measurements under unfavorable meteorological conditions and on a calculation based on data for discharge parameters obtained by the State Institute for the Design and Planning of Metallurgical Plants. The calculated data turned out to be slightly higher than the experimental ones. This may apparently be explained by the fact that the limited amount of observations did not permit the establishment of possible values of the highest concentrations.

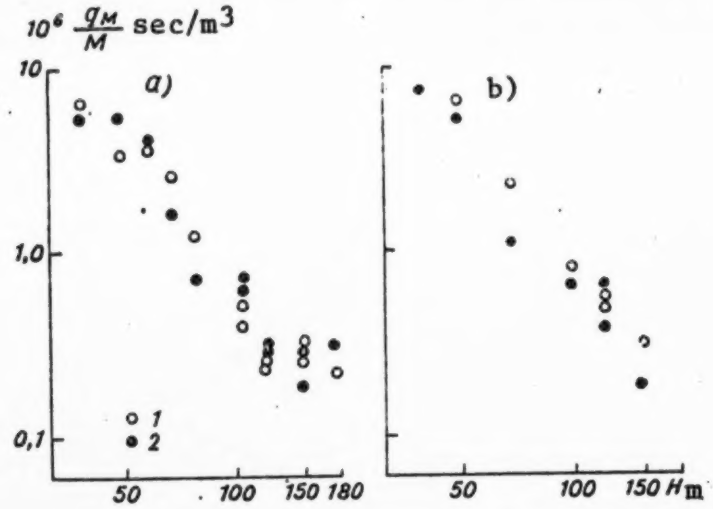

Fig. 7.

Graph of maximum concentrations of sulfur dioxide (a) and dust (b) normalized to the quantity of noxious substances discharged, versus stack height H.

1 - experimental data, 2 - calculated data

In 1962-1963 a substantial modernization of the Chimkent lead plant was carried out in order to purify the air reservoir in the adjacent areas; in particular, the discharge of sulfur dioxide into the atmosphere was considerably reduced, the height of stacks of the sintering section was raised from 70 to 120 m, etc. According to data of the State Institute for the Design and Planning of Nonferrous Metals Industry Establishments, the State Institute of Nonferrous Metals and the State Institute for the Design and Planning of Metallurgical Plants, the maximum concentration of sulfur dioxide q_M before the modernization of the plant was 10 mg/m^3, and after some modernization, it dropped to approximately 2 mg/m^3. Our calculations gave for q_M values, respectively, equal to 8.5 mg/m^3 and 2.5 mg/m^3.

Finally, we shall refer to the results of a survey of one of the major metallurgical plants in the south of the Ukraine, made in the summer of 1967. The distribution of dust up to a distance of 18 km from the plant is given in [16], based on observational data.

On the basis of observational data, the maximum dust concentration was 4 mg/m^3, and according to calculated data, 3 mg/m^3.

On the whole, it may be concluded that there is a satisfactory agreement between the calculated and experimental data, particularly if it is considered that only approximate values for the discharge parameters were known.

Some theoretical conclusions used in developing a method for calculating the dispersal of discharges from high stacks, in particular, conclusions of the theory of summer convective conditions, have been definitely confirmed by analyzing data of regular observations of pollution of city air reservoirs [41].

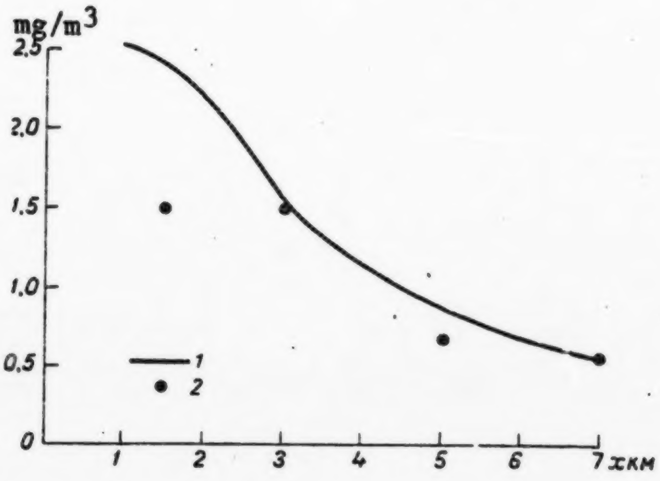

Fig. 8.

Highest sulfur dioxide concentrations at various distances from the Chelyabinsk Metallurgical Plant.

1 - calculated, 2 - experimental.

In summing up the discussion of the experimental verification of the method of calculation, let us note that the theoretical considerations of the patterns of dispersal of noxious discharges from various industrial enterprises in the atmosphere have been substantially confirmed for different meteorological conditions and climatic zones. The experimental data pertained to the most common ingredients of industrial discharges - sulfur dioxide and dust (ash); a complex characteristic of the discharge parameters is the quantity f introduced above (28); the experiments covered enterprises for which f reached 5-6, and sometimes even higher values. All of this forms a basis for the use of the method described for a broad class of operating and planned facilities, primarily for enterprises of the metallurgical, petroleum refining, chemical, and a number of other branches of industry.

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STUDY OF THE STRUCTURE OF A SMOKE JET AND DETERMINATION OF THE COEFFICIENT OF TURBULENT MIXING FROM THE VERTICAL DISTRIBUTION OF CONCENTRATIONS

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In the study of the diffusion of gases from plant stacks in the ground layer of the atmosphere, the usual methods of air sample collection may prove to be very difficult. Indeed, if the investigations are conducted in an urban residential district, it is extremely difficult and sometimes impossible to carry out the sampling above a smoke jet, which changes direction with variations in the wind direction. The difficulties increase if the sampling is performed above an invisible smoke plume such as is observed, for example, in the case of industrial plants producing synthetic fiber.

At the same time, in order to solve a number of technical problems connected with the installation of air pipes supplying clean air into the shop of industrial enterprises and in connection with some meteorological problems, it is of major interest to study the vertical concentration profile. The literature contains a relatively small amount of data on the study of the structure of smoke jets.

In the U.S.A. in 1943, Hewson and Gill [6] measured the concentration of sulfur dioxide in the Columbia River valley, using light monoplanes and captive balloons 1200 ft^3 in volume. In 1958, Stewart et al. [7] studied the vertical profile of concentrations in a radioactive plume using mobile balloons. However, all these studies were made relatively close to the source.

To overcome the above-mentioned obstacles, we attempted to develop the technique of sampling by using a helicopter. The great maneuverability of the helicopter in air, the possibility of measuring the concentrations in the smoke jet itself and the small investment of time on collecting the air samples at different points permit the use of the helicopter for the study of atmospheric pollution. The main elements of the planning and execution of observations from a helicopter consist in the following:

Selection of the type of helicopter as a function of its flight characteristics.

Study of the effect of the air currents created by the helicopter propeller on the sampling process, and study of the principle of arrangement of the instrumentation inside the helicopter.

Determination of the type of instruments used for sampling gaseous ingredients.

Study of the flight technique of the helicopter and collection of air samples.

Chemical analysis of the air samples.

Reduction of the data obtained to a form suitable for comparison with calculated values.

Correlation of the concentrations of gaseous ingredients with meteorological parameters.

In March 1967 in the city of Krasnoyarsk, an MI-1 helicopter was used for the study of the structure of a smoke jet. The study of the characteristics of the air currents generated by the helicopter propeller and their influence on the process of sample collection, as well as the arrangement of the instruments, were described in [4]. During the collection of representative samples from the helicopter, the suction apparatus for taking the samples was mounted in the nose of the helicopter and was moved slightly in front of the Pitot tube.

The air samples were collected for analysis for hydrogen sulfide (H_2S) and carbon disulfide (CS_2), discharged by the stacks of a synthetic fiber plant. The chemical analysis was performed in the water chemistry laboratory after the flights.

The smoke plume from the stacks of the synthetic fiber plant included a small visible portion (~100-200 m from the source), which aided in the determination of the direction of the smoke jet. At a given height and velocity of the flight (60-70 km/hr), the measurements were made at distances of 0.5, 1.5 and 3 km from the source and along the vertical at three heights depending on the ascent of the smoke jet; on the whole, for all the days of flight, the samples were taken at heights of 50, 100, 150, 200, 250 and 300 m above the earth's surface. The helicopter flew through the smoke jet in a perpendicular direction without going beyond it.

However, since at these distances the smoke jet was invisible, its width was calculated during the flight. Data on the initial visible portion of the jet were used for this purpose, and the coefficient of horizontal mixing was calculated in accordance with [5], and the width of the smoke plume was then calculated at different distances. The time of sample collection was 20 min. In five days, 196 samples for hydrogen sulfide and carbon disulfide were taken. At the same time, automobiles with mounted equipment were used to measure the concentrations of the same gases near the earth's surface. Since on the earth's surface the concentration was measured on the jet axis, in plotting the vertical profile of the impurity distribution it was necessary to switch from the integrated average value to the axial concentration.

In order to obtain this relationship, use may be made of calculations of the transverse distribution of the concentration in the jet as a function of the dispersion of horizontal fluctuations of the wind direction ϕ_0, in accordance with [2]. If the effective width of the smoke jet is denoted by R, and the concentration on the jet axis $q|_{y=0}=q_0(x, z)$, then

$$\bar{q}(x, z) = \frac{q_0(x, z)}{2R} \int_{-R}^{+R} \exp\left(-\frac{y^2}{2\varphi_0^2 x^2}\right) dy,$$

whence

$$q_0(x, z) = \frac{0{,}797 R \bar{q}(x, z)}{\varphi_0 x \operatorname{erf}\left(\frac{R}{\sqrt{2}\,\varphi_0 x}\right)}. \qquad (1)$$

As an example, Fig. 1a shows the vertical profile of the axial concentration of hydrogen sulfide (to the left of zero) and carbon disulfide (to the right of zero), which occurred in the smoke jet of 21 March 1967 at 10-11 hr and 15-16 hr at a distance of 500 m from the source. Fig. 1b shows the vertical profile of the temperature (1) and wind (2) for the same period of time.

Analysis of the graph (Fig. 1) shows that the concentration of carbon disulfide at a distance of 500 m from the source at 10-11 hr on the plume axis is almost 20 times the value at the earth's surface and approximately 50 times the MPC. The hydrogen sulfide concentration at the same distance from the source and at the same height is almost 30 times the MPC and 110 times the concentration at the earth's surface.

At the same time, analysis of the graph (Fig. 1) shows that the layer in which the smoke jet spreads is highly stratified, an inversion begins at the earth's surface, and its upper boundary is located at a height of 475 m.

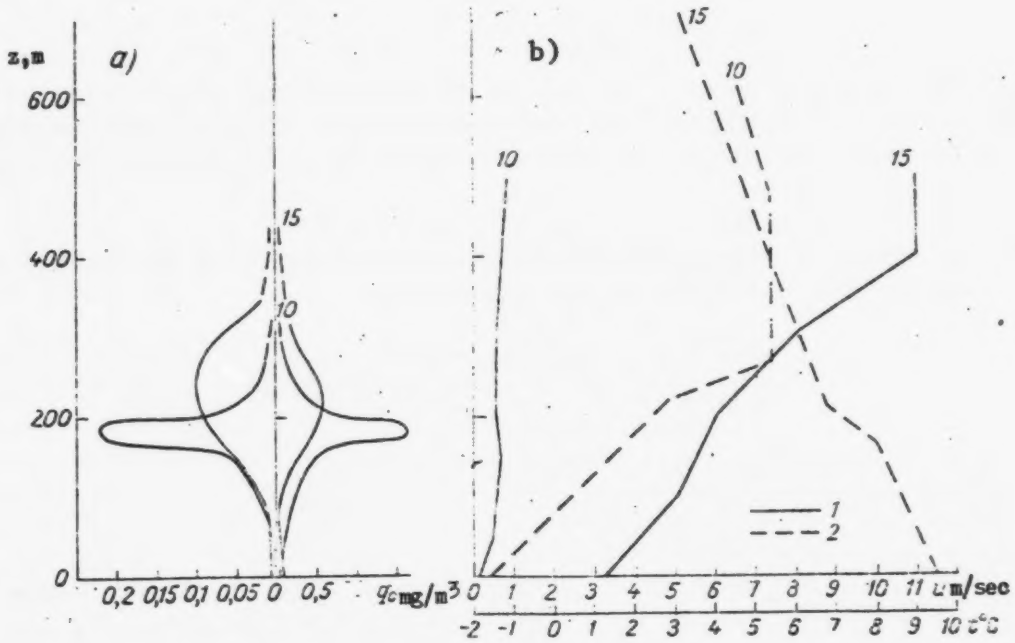

Fig. 1

It will be shown below that the coefficient of turbulent mixing in the layer of propagation of the smoke jet was 0.2-0.4 m^2/sec at that time. Because of such slight vertical mixing, the profile of the vertical concentration distribution is characterized by a large maximum on the axis of the smoke jet. By 15-16 hrs, a rearrangement of the temperature field took place. The layer of the atmosphere had now begun to be characterized by a stable state and a higher degree of turbulence ($k=8$ m^2/sec). In addition to the rearrangement of the temperature field and turbulent mixing, a change occurred in the distribution of the gaseous ingredients in height.

At 15-16 hrs, the concentration began to be more evenly distributed in the vertical direction and the dispersal of the impurity occurred much faster. Thus, the maximum carbon disulfide concentration on the axis of the smoke jet was only 20 times the MPC, and the hydrogen sulfide concentration, 13 times the MPC.

On the basis of the data obtained, an attempt was made to calculate the vertical coefficient of turbulent mixing from the distribution of the concentration in the smoke jet.

The equation of turbulent diffusion [1] for a linear source can be used for this purpose. When the impurity source is located at a sufficient height, where the exchange coefficient undergoes little change with height, for the calculation one can take the solution of the diffusion equation with constant coefficients

$$\bar{q}(x, z)=\frac{Q}{2\sqrt{\pi k x/u}}\left[e^{-\frac{(z-H)^2}{4kx/u}}+e^{-\frac{(z+H)^2}{4kx/u}}\right], \tag{2}$$

where Q is the capacity of the source; u is the average wind velocity; x is the distance from the source; k is the coefficient of turbulent mixing; H is the effective source height; z is the vertical distance from the earth's surface.

From the ratio of the integrated concentrations at three neighboring levels one can obtain a system of two equations:

$$\left.\begin{aligned}\frac{\bar{q}(x, z_2)}{\bar{q}(x, z_1)}&=e^{\frac{-z_2^2-z_1^2}{2H}S}\left(\frac{e^{z_2 S}+e^{-z_2 S}}{e^{z_1 S}+e^{-z_1 S}}\right);\\ \frac{\bar{q}(x, z_3)}{\bar{q}(x, z_2)}&=e^{\frac{-z_3^2-z_2^2}{2H}S}\left(\frac{e^{z_3 S}+e^{-z_3 S}}{e^{z_2 S}+e^{-z_2 S}}\right).\end{aligned}\right\} \tag{3}$$

The quantity S was determined from equation (4), which was solved numerically with a computer

$$\begin{aligned}\frac{z_3^2-z_2^2}{z_2^2-z_1^2}\left[(z_2-z_1)S+\ln\left(\frac{\bar{q}(x, z_2)}{\bar{q}(x, z_1)}\,\frac{1+e^{-2z_2 S}}{1+e^{-2z_1 S}}\right)\right]-\\ -\left[(z_3-z_2)S+\ln\left(\frac{\bar{q}(x, z_3)}{\bar{q}(x, z_2)}\,\frac{1+e^{-2z_3 S}}{1+e^{-2z_2 S}}\right)\right]=0.\end{aligned} \tag{4}$$

Thus, the coefficient of vertical turbulent mixing in the smoke jet may be determined from the formula

$$k=\frac{\left(z_j^2-z_i^2\right)\bar{u}}{4x\left\{\left[(z_j-z_i)\,S+\ln\left[\frac{\bar{q}\,(x,\,z_i)}{\bar{q}\,(x,\,z_j)}\,\frac{1+e^{-2z_jS}}{1+e^{-2z_iS}}\right]\right]\right\}},\qquad(5)$$

where i and j are consecutive numbers of the height levels at which the concentration is being determined.

The calculated values of the coefficient of turbulent mixing k are given in Table 1. For comparison, the same table lists values of the coefficient of turbulent mixing calculated from the formula $k=k_1h$, where h is the height of the ground layer of the atmosphere.

The coefficients of turbulent mixing at a height of 1 m were calculated by using data of meteorological observations for the same period according to M. I. Budyko's formula [3]. It is assumed that the coefficient of turbulent mixing increases linearly up to the height of the ground sublayer, and above this height the quantity h is assumed to be constant. For our calculations, h was taken as 100 m. Analysis of the data obtained shows a satisfactory agreement of the coefficients of turbulent mixing calculated from the distribution of concentrations in the plume and from the corresponding formula. The difference in the exchange coefficients of 21 March at 10 A.M. is obviously due to the fact that the layer in which the smoke jet was spreading was at that time subjected to the influence of the inversion state of the atmosphere, whereas the calculation of k_1 can be carried out only for an equilibrium state of the atmosphere.

Table 1

Date	Time, hr.	Distance From Source, m	k m^2/sec from the distribution of		$k=k_1h$ m^2/sec.
			Hydrogen Sulfide	Carbon Disulfide	
17 III 1967	11	500	4	4,2	5
	12	1500	—	3,5	
20	11	500	20	16	19
	13	3000	24	—	
21	10	500	0,2	0,4	14
	15	500	8	8	
22	13	500	—	14	11
	14	1500	—	18	
23	12	2000	4	4	2
	13	4000	2	1,3	

The good agreement of the data obtained also indicates a representative character of the concentrations measured in the smoke jet.

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